

SEK

From: Franco Battaglia <francesco.prof.battaglia@gmail.com>
Sent: Tuesday, August 5, 2025 1:57 AM
To: Steven Koonin <steven.koonin@googlemail.com>; Steven E Koonin <steven.koonin@nyu.edu>; koonin@stanford.edu
Subject: NYT

Hi, Steve.

A few days ago the NYT wrote an article that intended to be a rebuttal of the DOE report.

Today I wrote a rebuttal of the NYT article.

It is in Italian, but AI may easily translate it into English.

Best,

franco



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: John Christy <climateman60@gmail.com>
Sent: Tuesday, August 5, 2025 6:40 PM
To: Steven Koonin
Cc: Travis Fisher; Ross McKittrick; roywspencer@hotmail.com; Judith Curry
Subject: Re: a defense of CWG25 in the Italian press

Cliff Mass would be a critic on some of the topics, but a very helpful, honest critic. He's a councillor on the AMS board - he could have suggestions for critical yet helpful reviewers.

John C.

On Tue, Aug 5, 2025 at 5:33 PM Steven Koonin <steven.koonin@gmail.com> wrote:
And if we get a gusher of comments, we might benefit from someone with AI expertise to sort, triage, and summarize criticisms, chapter by chapter. And then, if necessary, identify suitable "realist" experts to help with a response.

Steven E. Koonin

On Aug 5, 2025, at 18:14, Steven Koonin <steven.koonin@gmail.com> wrote:

I think this is a good thing.

In formulating our responses, perhaps we could selectively enlist other climate realists.

Steven E. Koonin

On Aug 5, 2025, at 18:07, John Christy <climateman60@gmail.com> wrote:

From Cliff Mass - even AP is on the prowl. Why didn't they do this with the IPCC or NCA?

John C.

Hello,

We're Seth Borenstein and Michael Phillis, reporters on the climate and environment team at The Associated Press. As you know last week, the Trump administration's EPA proposed rescinding the 2009 Endangerment Finding on climate change. It did so with two documents. One was the actual EPA proposal and the other was the Department of Energy Climate Working Group's "A

Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate.” We have decided to ask the authors of every science-oriented reference in both documents about this. That’s why we are contacting you.

We’ve included links to both documents. Yes, they are long and we are sorry for that. Below you will see the page or chapter where your work was referenced for an easier guide.

Can you please by August 12, read these documents – or as much of the pertinent parts as you deem – and send us your thoughts and answer a few of the questions below.

We are purely looking at the science parts of these documents and that’s what we seek your thoughts on. In the EPA document, most of the overall science is from pages 75 (on the pdf reader at the top) through 85. We’ve also included EPA decision science highlights, but it may not be too comprehensive. Please tell us if we are missing something. The DOE document is mostly aimed at the science and its organization is fairly straightforward and it has an executive summary at the beginning. We are contacting well more than 100 scientists and experts like yourself to get a broad sense of the documents’ scientific accuracy so not everyone who answers will be quoted but if you do answer, and we would be appreciative, you will definitely help guide us to write a story with depth and authority.

You are referenced in: DOE Chapter 8

So now our questions:

What do you think of the overall quality of the DOE and EPA reports?

Did the sections of the report(s) that cited your work accurately and fairly portray it? Please elaborate.

Do the overall conclusions of the documents accurately portray the overall conclusions of your general body of work? Please explain why or why not.

Does the overall work and conclusions of the documents accurately portray the current, mainstream view of climate science? Please feel free to give details and explain what you consider important or not about this.

Was the selection of sources sufficiently current and representative of the best available science?

Do you consider the work and conclusions of the document to be biased in any way, or not? Please explain with examples.

On a scale of 0 to 100 with 100 being the best, how would you rate the EPA report? What about the DOE report?

If you were teaching an undergraduate class and your student delivered the EPA document as an assignment, what grade on the standard A to F scale would you give it? Why?

If you were teaching an undergraduate class and your student delivered the DOE document as an assignment, what grade on the standard A to F scale would you give it? Why?

Any other thoughts?

Thank you for your time and insight.

Sincerely,
Seth and Michael

On Tue, Aug 5, 2025 at 4:37 PM John Christy <climateman60@gmail.com> wrote:

Thanks Travis

We five have been through some rough times in the past 10-30 years, and to be given the microphone by such a remarkable leader on energy issues is nothing less than a high honor. Without getting trite, this may be the crowning achievement of some of our careers - and it was a long time coming when you've already passed three-score and ten before getting to this point. Thanks so very much for herding us through the labyrinth. Let's hope we set a template for other issues that need attention - rigorous analysis that is subject to transparent-scrutiny and acknowledged-uncertainties all along the way.

John C.

On Tue, Aug 5, 2025 at 3:16 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Ross, we had a quick call with the Secretary around 12:30. He thanked us all for our work, especially the CWG authors, and I emphasized your leadership role. Audrey said she and Chris would send you a video separately. I hope they do something ridiculous!

I'm attaching my write-up about this effort, which will be published at Cato and added to my Substack. If you have any concerns, please share them. I want to make sure everyone gets the credit they deserve and is comfortable with the way I talk about the effort.

I'll also run this by the DOE folks and try to publish it in the morning if possible.

On Tue, Aug 5, 2025 at 12:40 PM Ross McKittrick
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Sorry just seeing this. I'm on the road and unavailable until around 2.

On Tue, Aug 5, 2025 at 12:13 PM Travis Fisher
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Yes, look for a Google Meet link in one minute!

On Tue, Aug 5, 2025 at 12:07 PM Steven Koonin
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I think Ross is incommunicado until later this afternoon. Is the meeting happening and, if so, how to connect?

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Sent: Tuesday, August 5, 2025 10:37 AM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: roywspencer@hotmail.com; climateman60@gmail.com;
ross.mckitrick@gmail.com; Judith Curry <curry.judith@gmail.com>
Subject: Re: a defense of CWG25 in the Italian press

This is so cool!

I'm hearing from Audrey Barrios that the Secretary wants to schedule us all for a call at 12:15 p.m. ET today. Is everyone able to make that happen? Sorry for the short notice, and I don't have a clue what the call is about.

Ross, could you set this up as a Google meeting?

On Tue, Aug 5, 2025 at 8:44 AM Steven Koonin
<steven.koonin@gmail.com> wrote:

I also attach MS Copilot's translation to English.

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And most amusing is that the png shows Zeke's supplementary figure is now even more famous.

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To: Steven Koonin
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Subject: Re: a defense of CWG25 in the Italian press

The article is live: <https://www.cato.org/blog/why-i-helped-organize-department-energys-climate-report>. If anyone wants to suggest it to the editors at WUWT, that would be fine by me (I don't really know them).

Thank you all for welcoming me into the liaison role. It was truly a career highlight!

On Tue, Aug 5, 2025 at 8:27 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Travis – you write well – this is a fine piece.

It would be quite appropriate to see it on WUWT. And you might try publishing a somewhat shortened version in Real Clear Energy.

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Subject: Re: a follow-on thought

I'd want at least one statistician or econometrician.

On Wed, Jul 9, 2025 at 10:04 AM Judith Curry <curry.judith@gmail.com> wrote:

other NAS members:

Kerry Emanuel

Isaac Held

On Wed, Jul 9, 2025 at 6:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Another possible "peer" group would be some subset of the authors of NCA5 Chapters 1-3 and/or the (former) USGCRP or NCA5 leadership.

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Subject: Re: a follow-on thought

I agree, NASEM would be the appropriate group. The challenge would be to get NASEM to appoint a serious group of scientists, not like the group they appointed to review NCA5. Ideally the recommendations would come from BASC, not the CRC

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If the Secretary is interested in promoting a serious scientific discussion, he could charter NASEM to do a review of CWG25.

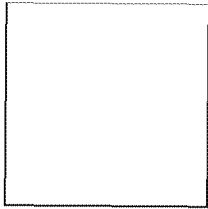
NASEM would find it difficult to say no, given their charter of advising the USG and current financial difficulties. I'd guess there'd be plenty of volunteers.

A review shouldn't take very long (after all, CWG was written in about 2 months). And shouldn't be very expensive (a committee of 5 volunteers, ½ a staff member, 15% overhead 😊)

Once NASEM produced a review, might even have a ½ - or 1-day workshop/conference to sort out differences.

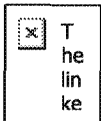
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I understand the temptation to have a group like NASEM undertake a review because the payoff, if they do a fair job of it, is additional credibility for the report. But we have to be realistic. NASEM has never dealt with climate change in anything like a fair or objective manner and they are not going to now. John and I watched up close when they made a total hash of the hockey stick inquiry. They rewrote the terms of reference to shield Mann, buried all the evidence confirming Steve's and my critique and then in the press conference allowed Gerald North to misrepresent the findings and claim vindication for Mann. Every time since then that they've looked at related topics they've deferred to the narrative, including in their review of NCA5.

When our report is released the narrative engineers will politicize it as the Trump report and look to the academic community to try to discredit it. If NASEM is asked to review it, while we can dream up a list of reasonable people to write the review, Marcia McNutt will be in charge. She will think of the headline she wants to see in the NYT and work backwards to the required report and the required team of writers. The press release might have lots of complimentary things to say but will include a killer quote like "While the report makes some valid points, including that climate science must continue to improve the models used to study climate dynamics, it is unfortunately biased and incomplete, and fails to provide a comprehensive summary of the current evidence regarding the seriousness of the climate crisis." Or something along those lines. Once they get to set the narrative and the headlines all the objections in the world from us will count for naught.

I reiterate my suggestion that the report be published by the DoE and then submitted by Sec Wright as a comment on the EF filing by the EPA.

On Wed, Jul 9, 2025 at 12:26 PM Judith Curry <curry.judith@gmail.com> wrote:

Graeme Stephens is another good one (not economist, radiation and general climate), he is NAE

On Wed, Jul 9, 2025 at 8:59 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I know Andrew Gelman at Columbia is a statistician who's been critical of statistical methods in climate:

https://en.wikipedia.org/wiki/Andrew_Gelman

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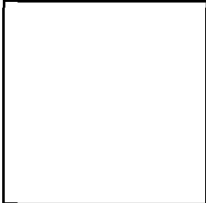
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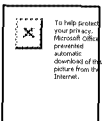
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There will be a lot of comments on the report. Could these comments be filtered down to a few, given to the Secretary and he let him direct us to address concerns that he sees are important to his role?

John C.

On Thu, Jul 10, 2025 at 10:22 AM Judith Curry <curry.judith@gmail.com> wrote:

Ok, convinced again by Ross. The secy asked us to write a report, and here it is. We have opened up a website for public comments.

On Thu, Jul 10, 2025 at 7:49 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I don't like the idea of releasing the report and at the same time saying we've asked for it to be reviewed. Apart from looking like we're not confident in our work, it creates a terrible strategic vulnerability. All it would take is for one proposed reviewer to refuse and then tell the press he wasn't willing to lend his name to the process, and then the story would be all about the supposedly dodgy process, not the report contents. This has been the playbook to discredit everything coming out of Benny Peiser's group in the UK. And I remember when a US think tank (Cato? can't remember) asked a bunch of outside experts to write some commentaries on the GW topic and offered to pay them, thinking this was a way to gain some credibility, and instead the experts went to the press and suddenly the story was about skeptics supposedly trying to pay off scientists.

It is a sad reality that the current situation is way too politicized and polarized for us to get an objective review from anyone with name recognition. Not only is climate change a hopelessly fraught topic, but this project is connected to the Trump admin making it radioactive inside academia. While I can think of economists capable of writing intelligent reviews (like Bob Mendelsohn, Matt Kahn and Richard Tol) I am not convinced any of them would want to in the present environment.

I would rather the report be released as-is, which is the form in which the Secretary requested it. People will complain that it's not "peer-reviewed" aka approved by the gatekeepers but we can't solve that problem in the next 2 weeks. We all know who will love it and who will hate it and for everyone else we can only hope they read it with an open mind. A reformed NCA6 process would be the venue to try and reform the larger conversation around climate change, if such be possible.

On Thu, Jul 10, 2025 at 10:27 AM Judith Curry <curry.judith@gmail.com> wrote:

Here is a proposal. Secy Wright (or whoever) invites ~10 leading scientists to review this (see attached draft letter), issue the invites before the report is published and the fact that such individuals (not named) have been invited can be mentioned in the press release

These should be 90% consensus leaning, but independent thinkers (we can probably sneak in RP Jr)
Here is a list to consider:

Bill Collins (LLNL)
Isaac Held (Princeton, NAS)
Clara Deser (NCAR, NAS)
Graeme Stephens (NASA JPL, NAE)
Elizabeth Barnes (CSU, NASEM BASC; note she is also good with statistics)
Kerry Emanuel (MIT, NAS)
Dan Shrag (Harvard, NAS?)
Richard Newell (economist)
Pielke Jr
(statistician)
(carbon cycle person)

I suggest 100% US scientists (Canadians are fine!) Note I am close personal friends with tim palmer, his agenda is 100% needing monstrous supercomputers for very high res climate models, he also thinks ECS is >5C because the UKMO weather model when used in climate mode has ECS>5C performs better in terms of predicting rainfall; my arguments explaining why these parameterizations work for weather but not climate have fallen on deaf ears.

On Thu, Jul 10, 2025 at 7:09 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:
Ok I'm convinced NASEM is hopeless, which is really unfortunate.

I'm open to ideas on how best to comply with the new directives. See the OSTP memo here:
<https://www.whitehouse.gov/wp-content/uploads/2025/03/OSTP-Guidance-for-GSS-June-2025.pdf>

One sticking point is that DOE will not have its own guidelines in place until September, and we need to be ready to publish the CWG report by July 21.

My current thinking is to set up a round of expert review concurrent with the public comment period and signal at each step that we intend to comply with the EO, etc.

The main task in choosing experts is to ensure we aren't cherry-picking. This is where we might get into a red/blue team exercise, although it's probably best to include lots of "purple" too (to abuse the red-blue analogy). You know what I mean—apolitical experts, etc.

Regarding process and personnel, we're losing Seth for a few weeks to the NRC, and I need to get myself back to Cato soon (as soon as we publish the CWG report). Josh, Seth, and you all will be the glue to hold this process together as you respond to comments. We also need to get Steve in place at USGCRP.

In good news, DOE's undersecretaries are being sworn in and can begin work now. I plan to loop in a new advisor in the office of the undersecretary for science to help with this effort—he starts this coming Monday.

I'm excited for the report to hit daylight. In the event we have to publish on short notice, would someone please reply here with the version of the report we want to release? Keep in mind the EPA rulemaking references the findings of the CWG report by page number, so we should take care not to change those from the May version.

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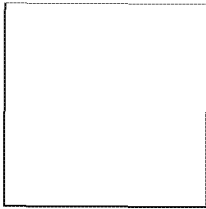
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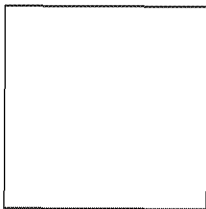
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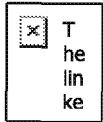
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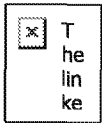
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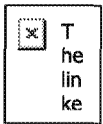
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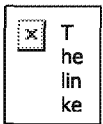
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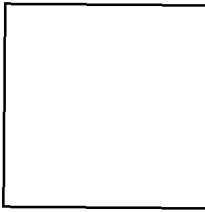
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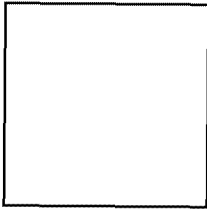
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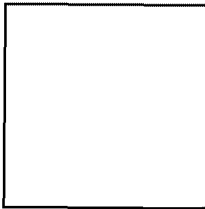
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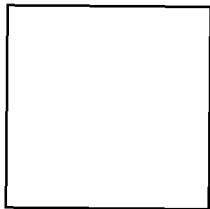
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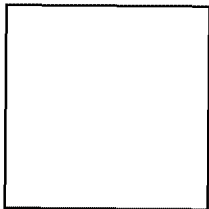
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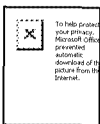
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One complication is that the implementing guidelines / regulations seem to be changing based on recent EOs and won't be finalized for a couple of months.

Here's a place to start, noting that these standards will probably change to incorporate recent EOs and OSTP guidance:

<https://www.energy.gov/cio/department-energy-information-quality-guidelines>

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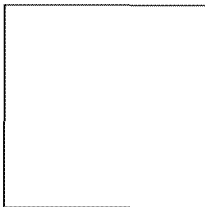
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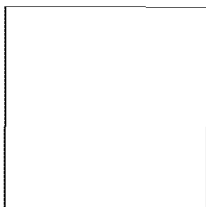
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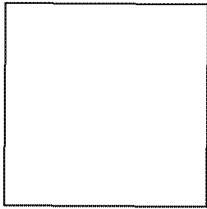
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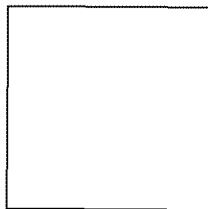
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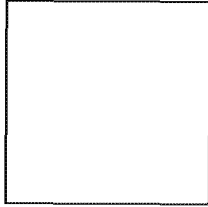
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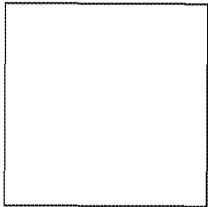
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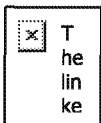
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From: Judith Curry <curry.judith@gmail.com>
Sent: Thursday, July 10, 2025 1:08 PM
To: Travis Fisher
Cc: Steven Koonin; John Christy; Ross McKittrick; Roy Spencer; Josh Loucks
Subject: Re: a follow-on thought
Attachments: DOE IQA.docx

Very helpful, i went through the doc (see attached, i clipped relevant text).

It seems that our Report qualifies as "influential information". Main concern is transparency and reproducibility (i think we score high on this).

Main responsibility in pre-publication period is internal review by DOE

On Thu, Jul 10, 2025 at 9:28 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

I agree with the need to confront this head-on.

One complication is that the implementing guidelines / regulations seem to be changing based on recent EOs and won't be finalized for a couple of months.

Here's a place to start, noting that these standards will probably change to incorporate recent EOs and OSTP guidance:

<https://www.energy.gov/cio/departments-energy-information-quality-guidelines>

Further, if the goal is to satisfy EPA's standards in the hopes of being used in EPA rulemakings, we may have two different moving targets to hit (DOE regs and EPA regs).

On Thu, Jul 10, 2025 at 11:53 AM Judith Curry <curry.judith@gmail.com> wrote:

Travis, can you summarize all the federal requirements for unbiased peer review?

We need to confront this one head on. Open comments and response may actually be the best way to handle this in the current political environment surrounding climate change

On Thu, Jul 10, 2025 at 8:46 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Rest assured you all won't have to read every comment!

We still have the task of ensuring that the final report satisfies science standards, possibly including HISA.

Do you all think responding to public comments will satisfy all the relevant standards?

On Thu, Jul 10, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Filtering/summarizing is a suitable task for an AI agent.

From: John Christy <climateman60@gmail.com>

Sent: Thursday, July 10, 2025 11:40 AM

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There will be a lot of comments on the report. Could these comments be filtered down to a few, given to the Secretary and he let him direct us to address concerns that he sees are important to his role?

John C.

On Thu, Jul 10, 2025 at 10:22 AM Judith Curry <curry.judith@gmail.com> wrote:

Ok, convinced again by Ross. The secy asked us to write a report, and here it is. We have opened up a website for public comments.

On Thu, Jul 10, 2025 at 7:49 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I don't like the idea of releasing the report and at the same time saying we've asked for it to be reviewed. Apart from looking like we're not confident in our work, it creates a terrible strategic vulnerability. All it would take is for one proposed reviewer to refuse and then tell the press he wasn't willing to lend his name to the process, and then the story would be all about the supposedly dodgy process, not the report contents. This has been the playbook to discredit everything coming out of Benny Peiser's group in the UK. And I remember when a US think tank (Cato? can't remember) asked a bunch of outside experts to write some commentaries on the GW topic and offered to pay them, thinking this was a way to gain some credibility, and instead the experts went to the press and suddenly the story was about skeptics supposedly trying to pay off scientists.

It is a sad reality that the current situation is way too politicized and polarized for us to get an objective review from anyone with name recognition. Not only is climate change a hopelessly fraught topic, but this project is connected to the Trump admin making it radioactive inside academia. While I can think of economists capable of writing intelligent reviews (like Bob Mendelsohn, Matt Kahn and Richard Tol) I am not convinced any of them would want to in the present environment.

I would rather the report be released as-is, which is the form in which the Secretary requested it. People will complain that it's not "peer-reviewed" aka approved by the gatekeepers but we can't solve that problem in the next 2 weeks. We all know who will love it and who will hate it and for everyone else we

can only hope they read it with an open mind. A reformed NCA6 process would be the venue to try and reform the larger conversation around climate change, if such be possible.

On Thu, Jul 10, 2025 at 10:27 AM Judith Curry <curry.judith@gmail.com> wrote:

Here is a proposal. Secy Wright (or whoever) invites ~10 leading scientists to review this (see attached draft letter), issue the invites before the report is published and the fact that such individuals (not named) have been invited can be mentioned in the press release

These should be 90% consensus leaning, but independent thinkers (we can probably sneak in RP Jr)

Here is a list to consider:

Bill Collins (LLNL)

Isaac Held (Princeton, NAS)

Clara Deser (NCAR, NAS)

Graeme Stephens (NASA JPL, NAE)

Elizabeth Barnes (CSU, NASEM BASC; note she is also good with statistics)

Kerry Emanuel (MIT, NAS)

Dan Shrag (Harvard, NAS?)

Richard Newell (economist)

Pielke Jr

(statistician)

(carbon cycle person)

I suggest 100% US scientists (Canadians are fine!) Note I am close personal friends with tim palmer, his agenda is 100% needing monstrous supercomputers for very high res climate models, he also thinks ECS is >5C because the UKMO weather model when used in climate mode has ECS>5C performs better in terms of predicting rainfall; my arguments explaining why these parameterizations work for weather but not climate have fallen on deaf ears.

On Thu, Jul 10, 2025 at 7:09 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Ok I'm convinced NASEM is hopeless, which is really unfortunate.

I'm open to ideas on how best to comply with the new directives. See the OSTP memo here:

<https://www.whitehouse.gov/wp-content/uploads/2025/03/OSTP-Guidance-for-GSS-June-2025.pdf>

One sticking point is that DOE will not have its own guidelines in place until September, and we need to be ready to publish the CWG report by July 21.

My current thinking is to set up a round of expert review concurrent with the public comment period and signal at each step that we intend to comply with the EO, etc.

The main task in choosing experts is to ensure we aren't cherry-picking. This is where we might get into a red/blue team exercise, although it's probably best to include lots of "purple" too (to abuse the red-blue analogy). You know what I mean—apolitical experts, etc.

Regarding process and personnel, we're losing Seth for a few weeks to the NRC, and I need to get myself back to Cato soon (as soon as we publish the CWG report). Josh, Seth, and you all will be the glue to hold this process together as you respond to comments. We also need to get Steve in place at USGCRP.

In good news, DOE's undersecretaries are being sworn in and can begin work now. I plan to loop in a new advisor in the office of the undersecretary for science to help with this effort—he starts this coming Monday.

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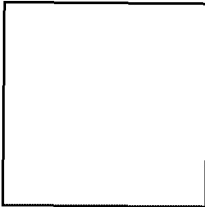
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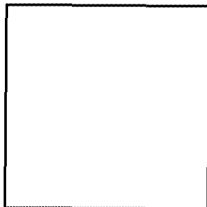
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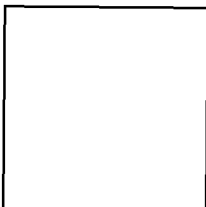
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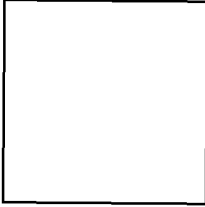
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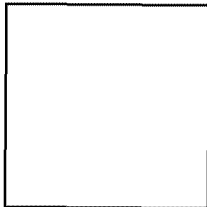
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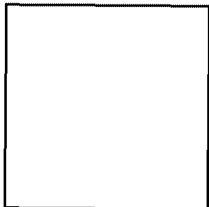
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This report qualifies as “influential information” under DOE’s IQA guidelines

“influential” information should meet the highest standards of quality and transparency (consistent with countervailing considerations such as confidentiality) and data must be capable of reproduction by a qualified individual outside of the agency.

DOE revisited its parameters for identifying “influential information,” as instructed by OMB-M-19-15, and believes that, consistent with the OMB directive, DOE’s definition of “influential information” provides sufficient guidance for program managers for determining the amount and type of pre-dissemination review necessary.

2. *Peer review.* DOE complies with OMB’s *Final Information Quality Bulletin for Peer Review*, which states that “peer review typically evaluates the clarity of hypotheses, the validity of the research design, the quality of data collection procedures, the robustness of the methods employed, the appropriateness of the methods for the hypotheses being tested, the extent to which the conclusions follow from the analysis, and the strengths and limitations of the overall product,” 70 FR 2664-2665 (Jan. 14, 2005). DOE Elements, along with National Laboratories, may use peer review panels or comparable assessment processes, to objectively evaluate programmatic, technical, scientific, business methods, analytic results, and other findings. DOE Elements may rely on internal or external peer review panels and processes to make these evaluations. In cases where previously determined influential information has changed significantly, the DOE Element with authority over the data should consider whether a second peer review panel or comparable assessment process should be convened to evaluate the objectivity and reliability of the changed data, as appropriate given the program’s intended use of the modified information. DOESN’T SEEM RELEVANT FOR OUR REPORT

11. Subject to public comment means that DOE has made the information available for comment by members of the public, preliminary to making a final determination, through a notice in the *Federal Register* including, but not limited to, a notice of inquiry, an advance notice of proposed rulemaking, a notice of proposed rulemaking, a notice reopening or extending a comment period due to receipt of new information, a notice of availability of a draft environmental impact statement, a notice of a proposed information collection, or any other *Federal Register* notice that provides an opportunity for comment by members of the public regarding the quality of information on which a final determination may be based.

Applicability to information from a non-Federal government source. These Guidelines apply to information under the control and management of the Department and its Element offices. Information is not under the control of the Department if the Department is not granted the authority to modify or change such data without the consent of the original source. In the interest of transparency or public awareness, DOE may make publicly available information provided by a non-Federal government source. For example, the Department may post on its website information regarding Native American Tribal infrastructure projects utilizing DOE-provided energy grants. Such information is produced and owned by the participating Tribal entities and made available to a broader audience through the DOE website, but DOE does not have authority to change or modify the data. NOT CLEAR IF CWG IS NOT GOVT SOURCE???

In a scientific, financial, or statistical context, the original and supporting data should be generated, and the analytical results developed, using sound statistical and research methods. If the data and analytical results have been subjected to formal, independent, external peer review, the information may generally be presumed to be of acceptable objectivity. ABOVE RELATES TO SCREEN SHOTS OF PREVIOUSLY PUBLISHED PAPERS However, this presumption is rebuttable based on a persuasive showing by a member of the public seeking correction of information in a particular instance. If DOE Element-sponsored peer review is employed to help satisfy the objectivity standard, the review process employed should meet the general criteria for competent and credible peer review found in OMB’s *Final Information Quality Bulletin for Peer Review*, issued in December 2004 and posted at (<https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/memoranda/2005/m05-03.pdf>)

Pre-dissemination review procedures. Before disseminating information to members of the

public, the originating office of the DOE Element is responsible for ensuring that the information is consistent with the OMB and DOE guidelines and that the information is of adequate quality for dissemination. If the information is influential financial, scientific, or statistical information, then, to the extent practicable, the DOE Element should provide for higher level review of the originating office's conclusions. Each DOE Element should identify for the CIO a high ranking official who is responsible for ensuring the accountability of the DOE Element's program offices in reviewing information to be disseminated to members of the public under the OMB and DOE guidelines. ~~SEEMS INTERNAL DOE REVIEW IS ALL WE NEED AT THIS POINT~~

As a matter of good and effective information resources management, DOE Elements may develop and post on their websites supplemental guidelines for the process they will follow for reviewing the quality (including objectivity, utility and integrity) of information before it is disseminated. The DOE IQA Guidelines website will provide a central repository for DOE Element supplemental guidance related to quality review processes. DOE Elements should treat information quality as integral to every step of development of information, including creation, collection, maintenance, and dissemination. This process will enable every DOE Element to substantiate the quality of the information it has disseminated through documentation or other means appropriate to the information.

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Sent: 7/9/2025 4:26:27 PM
To: Steven Koonin [steven.koonin@gmail.com]
CC: Ross McKittrick [ross.mckittrick@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; John Christy [climateman60@gmail.com]; Roy Spencer [roywspencer@hotmail.com]; Josh Loucks [loucksj14@gmail.com]
Subject: Re: a follow-on thought

Graeme Stephens is another good one (not economist, radiation and general climate), he is NAE

On Wed, Jul 9, 2025 at 8:59 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I know Andrew Gelman at Columbia is a statistician who's been critical of statistical methods in climate:

https://en.wikipedia.org/wiki/Andrew_Gelman

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Wednesday, July 9, 2025 11:39 AM
To: Judith Curry <curry.judith@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>
Subject: Re: a follow-on thought

I'd want at least one statistician or econometrician.

On Wed, Jul 9, 2025 at 10:04 AM Judith Curry <curry.judith@gmail.com> wrote:

other NAS members:

Kerry Emanuel

Isaac Held

On Wed, Jul 9, 2025 at 6:52 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Another possible "peer" group would be some subset of the authors of NCA5 Chapters 1-3 and/or the (former) USGCRP or NCA5 leadership.

SEK

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I agree, NASEM would be the appropriate group. The challenge would be to get NASEM to appoint a serious group of scientists, not like the group they appointed to review NCA5. Ideally the recommendations would come from BASC, not the CRC

On Tue, Jul 8, 2025 at 6:05 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

This idea would get us a lot closer to peer review, as opposed to relying exclusively on public comments. I like it!

Are there other, similarly situated peer groups we should consider? I plan to propose this soon, but I'll give us all a few days to consider it.

On Tue, Jul 8, 2025 at 7:46 PM Steven Koonin <steven.koonin@gmail.com> wrote:

If the Secretary is interested in promoting a serious scientific discussion, he could charter NASEM to do a review of CWG25.

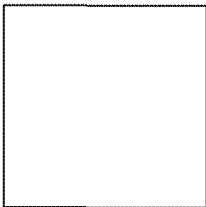
NASEM would find it difficult to say no, given their charter of advising the USG and current financial difficulties. I'd guess there'd be plenty of volunteers.

A review shouldn't take very long (after all, CWG was written in about 2 months). And shouldn't be very expensive (a committee of 5 volunteers, ½ a staff member, 15% overhead ☺)

Once NASEM produced a review, might even have a ½ - or 1-day workshop/conference to sort out differences.

SEK

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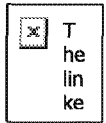


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Sent: Monday, June 2, 2025 10:33 AM
To: Steven Koonin
Cc: John Christy; Travis Fisher; Roy Spencer; Ross McKittrick; Josh Loucks
Subject: Re: an early take on NCA5 Chapter 1
Attachments: NCA Intro.docx

See attached (note, this is pretty much all i can do for next 24 hours, need to be in hurricane report mode). Let me know what you think

On Sun, Jun 1, 2025 at 3:21 PM Steven Koonin <steven.koonin@gmail.com> wrote:
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The fifth National Climate Assessment (NCA5) by the U.S. Global Change Research Program (USGCRP) fails to meet the statutory requirements of the Global Change Research Act of 1990 (GCRA)¹ and violates Executive Order 14303, “Restoring Gold Standard Science” (EO14303).²

Under the GCRA’s terms, the USGCRP must issue periodic assessments to update policymakers on a variety of global changes. To fulfill its statutory mission to “describe and understand” the Earth’s systems and human impacts on them, such a report should be objective. However, USGCRP assessments have increasingly served to justify predetermined policy and societal actions.

Politicization of climate science is endemic owing to the international imperative of NetZero. Even in this context, the NCA5 is far more biased than the IPCC AR6 WG1 Report. Evidence of bias in the NCA5 includes:

Biased authors. The NCA5’s list of 500 authors was lauded by the NASEM review (footnote) for its racial diversity. However, this list did not include any university or government scientists whose research and perspective challenged the prevailing narrative. Instead, they included N authors employed by NGOs, most of which are political advocacy organizations. They did not include any authors from industry. **CHECK**.

Biased attribution. The NCA5 implicitly assumes that all warming is caused by anthropogenic emissions. Further, they attribute many impact drivers and extreme weather events to anthropogenic emissions, well beyond the IPCC AR6 WG1 assessment

Cherry picking of US weather and climate data. In most analyses, the NCA5 neglected to include data prior to 1950 (and in some cases prior to 1970), eliminating from consideration the 1930s – a decade with the worst heat waves and droughts and even the worst US landfalling hurricane.

Lack of reproducibility. **JOHN CHRISTY**

Assumption that warming is dangerous. The NCA5 neglects benefits from more CO₂ in the atmosphere and from warming.

Implausible extreme emissions scenarios. It is now well known that the extreme emissions scenarios are implausible – UN climate negotiators (COP) have dropped the extreme emissions scenarios from their analyses and projections since 2021 (I have a link for this). Nevertheless, a word search of the NCA5 shows that a majority of the mentions were of the extreme emissions scenario

¹ <https://www.globalchange.gov/about-us/legal-mandate>

² <https://www.federalregister.gov/documents/2025/05/29/2025-09802/restoring-gold-standard-science>

Uncritical acceptance of climate model outputs. The NCA5 uncritically accepts climate model outputs for region climate impact assessments and 21st century projections. This uncritical acceptance is not justified, and is at odds with IPCC AR6 WG1 Report (Chapter 10)

Overconfidence of conclusions. The terminology NCA5 uses for confidence levels is inflated. NCA5 conclusions with medium confidence are justified by “Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.) competing schools of thought. NCA conclusions with high confidence are justified by “Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus (NOTE THIS TEXT IS FROM NCA4, DOUBT IT CHANGED FOR 5

Failure to assess uncertainties. The NCA5 briefly mentions uncertainties for each major conclusion in a traceability account (in the Appendix?). These uncertainties are not included in the main text and do not appear to influence the conclusions. The main text neglects obvious representations of uncertainty such as the statistical significance of trends CHECK I KNOW THE NCA4 had a traceability account for the NCA4, assume they also did for NCA5

Focus on a single solution. The document advocates for a single solution – replacement of fossil fuels with wind and solar power CHECK

The magnitude of the bias and lack of objectivity in the NCA5 Report is evidence by comparing it with our DOE document. This document was authored by five scientists whose research and perspectives challenge the prevailing narrative – a category of author that was not included by the NCA5. The DOE included topics and data that were not included in the NCA5, and drew substantially different conclusions from the NCA5 ETC

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It would not be wise or feasible for us to try to dismiss the entire NCA5. My preferred assignment is to focus on the public-facing summaries and website. I think it's fair to look at the tone and content of those things. I doubt the 500 scientists had much to do with them anyway and aren't likely to defend them. Chances are if we waded through all 2,000 pages (or whatever) there would be lots we'd agree with or at least not find objectionable. But for a document intended to equip policy makers and inform the public it's no defence if they said something sensible halfway down paragraph 3 on page 1,455, if the websites and PR stuff are all one-sided propaganda. A big issue is what they choose to focus on and what they choose to ignore, and our group is ideally constituted to notice those things.

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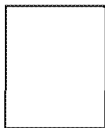
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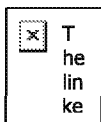
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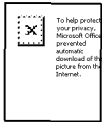
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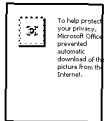
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I'm happy to adjust as needed, but 3pm ET tomorrow works for me.

Regarding the what and the why of the task, we can discuss more details on the call, but my understanding is that we should critically review NCA 5 (at whatever level of detail is feasible in a period of a couple of weeks) through the lens of the statute, the executive order, and the DOE report.

As of right now, we should write this document as a response to a request from OSTP, along the lines of the scoping memo Ross shared. There is a chance OSTP might want to claim authorship, but my hunch is that whatever you all produce next will be another group report with each of your names on it.

The next best alternative is for one of you to take the helm at GCRP and publish the next document as something of a policy statement by the new GCRP director. (That's actually my first-best approach, but I completely understand if it's too big of an ask or if certain members of this group are too Canadian.)

On Mon, Jun 2, 2025 at 9:51 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Sent a meeting link for 3 PM. I couldn't remember what time we agreed to and I know Roy can't be there but I thought it was around 3.

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At least some politicians are trained as lawyers and understand the concepts of evidence, proof, etc. I think we could reach them. And in the current political/culture climate, everyone is suspicious of being lied to. Worth a try, in my opinion (and experience).

Anyway, we should discuss on tomorrow's call. Do we yet have a time and video link?

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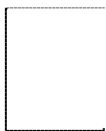
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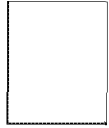
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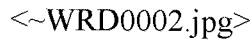
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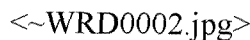
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Here is a suggested framing from Ch 10 of my book, which could help with the fitness for policy making

An important element of characterizing risk is evaluating the strength of knowledge. Concerns about strength of the climate change knowledge base are raised by people questioning aspects of the IPCC's assessment that are used to infer climate risk. The IPCC approach is based on judgment of the available evidence and agreement among experts. More sophisticated knowledge characterizations for risk management include:

Terje Aven, "Improving Risk Characterisations in Practical Situations by Highlighting Knowledge Aspects, with Applications to Risk Matrices," Reliability Engineering & System Safety 167 (November 2017): 42–48, <https://doi.org/10.1016/j.ress.2017.05.006>. (Note: Aven is arguably the Dean of international risk science)

(i) The degree to which the assumptions made are reasonable/realistic based on our background knowledge—concern about the focus on implausible emissions scenarios RCP8.5/SSP5–8.5

(ii) The degree to which data/information exists and are reliable and relevant—the historical and paleo database is inadequate for a complete characterization of natural climate variability on multi-decadal to millennial time scales

(iii) The degree to which there is disagreement among experts (including those from different environments or academic fields)—attempts to suppress disagreement and alternative perspectives among experts

(iv) The degree to which the phenomena involved are understood and accurate models exist—concerns about the fidelity and utility of climate models

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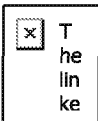
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Attachments: NCA5_daily_precip_v01.docx

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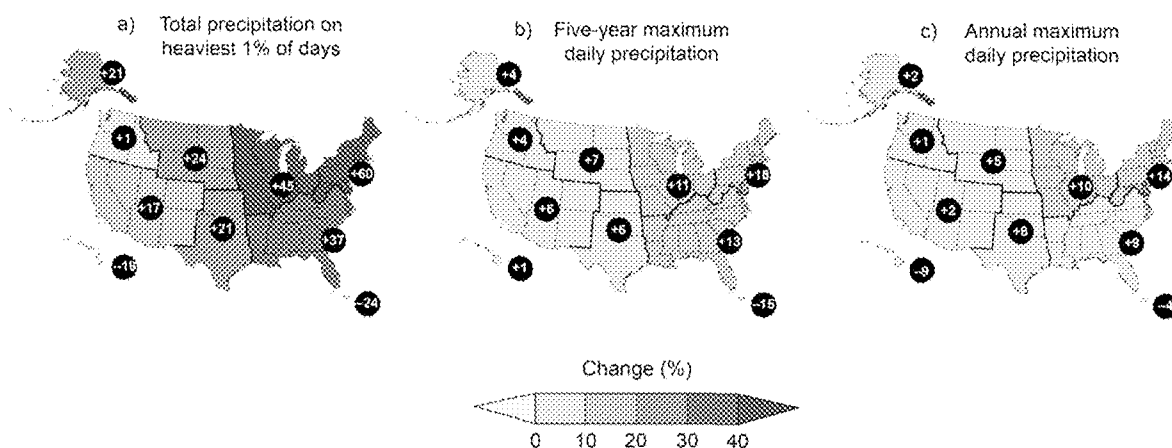


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Discussion of changes in extreme precipitation events in NCA5

The NCA5 apparently was not subjected to the kind of rigorous peer-review normally applied to documents of its alleged significance. For example, here is Fig. 2.8 from NCA5 indicating heavy, short-duration precipitation events are becoming more frequent and severe.

Observed Changes in the Frequency and Severity of Heavy Precipitation Events



Heavy precipitation events are becoming more frequent and intense across much of the country.

FIGURE 2.8. The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern part of the continental US, with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (a) total precipitation falling on the heaviest 1% of days, (b) daily maximum precipitation in a 5-year period, and (c) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict percent changes at the regional level. Data were not available for the US Affiliated Pacific Islands and the US Virgin Islands. Figure credit: (a) adapted from Easterling et al. 2017;¹²⁶ (b, c) NOAA NCBI and CISSS NC.

The NCA5 concludes from this evidence and selective model output,

There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.^{126,127}

A critical review would have asked questions of Fig. 2.8 and the conclusion such as;

- (1) why begin with 1958 when measurements are available from the late 19th century?
- (2) given that hydrologic/precipitation events are subject to “Long-Term Persistence” (LTP) where long dry- and wet-spells are common features, shouldn’t one expect natural changes over any 64-year period (1958-2021)?

- (3) related to (2), are these percentage changes significant or do they lie within the range of the enormous natural variability of such metrics?
- (4) was an evaluation made of the model simulations that led to the conclusion that human emissions contributed to the changes?

The Diffenbaugh et al. 2018 citation [126] used an even shorter observational window of 1961-2005 than NCA5 to determine “historical” trends, then analyzed output from the implausible RCP8.5 climate model simulations to claim changes were likely human-caused.

The Kirchmeier-Young 2020 citation [127] utilized observations for 1961-2010 and for climate model output, again the implausible RCP8.5 simulations to claim increases in extreme events *were related to human emissions. Further, the model output had to be multiplied by a “scaling factor” to force agreement with the magnitudes of historical observations of extreme events, a factor which varied from 0.4 to 2.2, indicating models are inadequate at depicting the scale of actual heavy precipitation events.* Furthermore, the focus of the analysis was on the CanESM2 CMIP-6 model, one that produced global atmospheric temperature trends that were a factor of 2.5 too positive compared with observations due to excessive sensitivity to GHG forcing (+0.43 vs. +0.17 °C/decade, 1979-2024).

A critical review would have pointed out the impropriety of using (a) “historical” results for change-analysis from short data periods, (b) implausible emissions scenarios and (c) an extremely sensitive model. To attribute the qualifier “robust” to results from such an analysis is rather bold, as well as inappropriate.

To understand the character of recent changes against the background of a better-quantified natural variability we constructed continuous daily precipitation datasets for stations within four regions; (1) Pacific Coast (1893ff) where AR6 indicated an increase in Atmospheric River events had been suggested since 1948, and three regions that NCA5 indicates as experiencing increases in short-duration heavy events; (2) Upper Midwest (1893ff), (3) Humid Southeast (1872ff) and (4) Northeast (1888ff). Surprisingly, NCA5 did not perform significance-testing on the alleged changes.

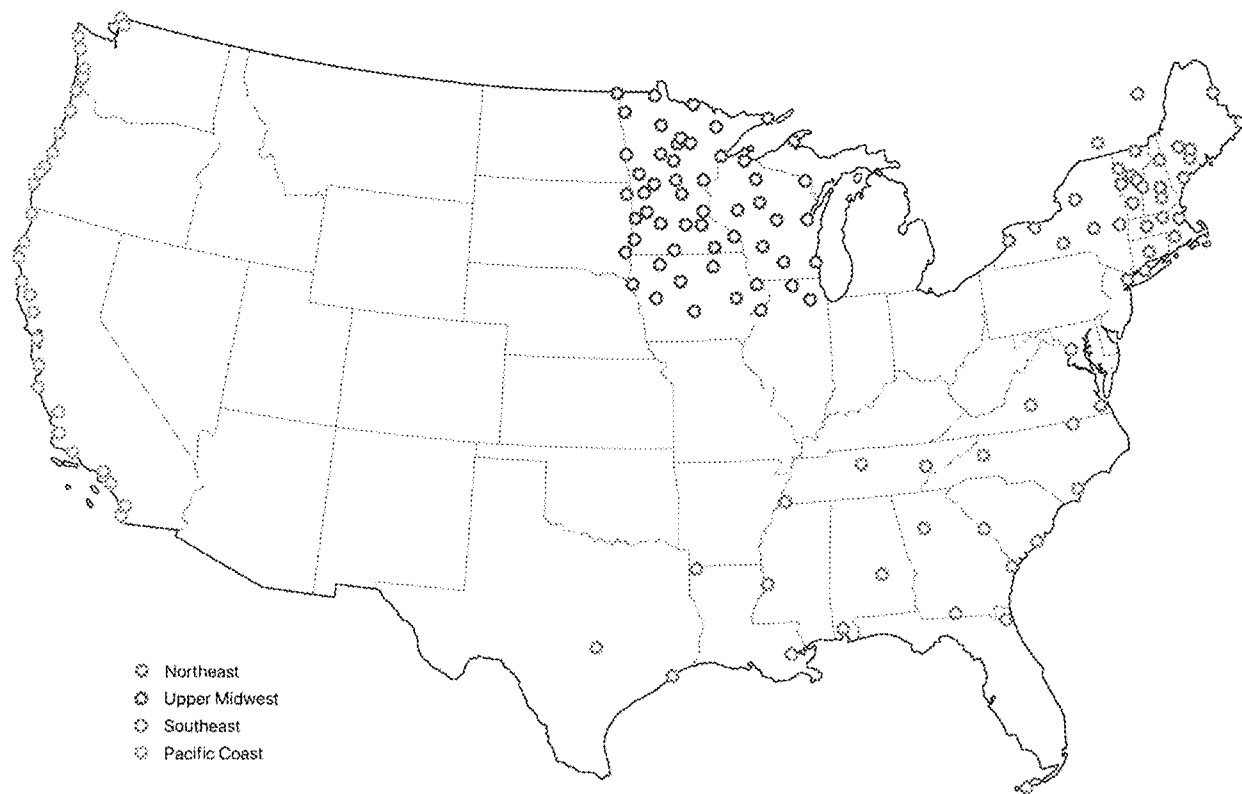


Figure. Location of stations utilized in this study.

Following McKittrick and Christy 2019 (who found no significant changes in the West and Southeast with observations beginning in the late 19th century) we apply the more appropriate statistical analysis which characterizes LTP for precipitation events to determine if these changes are significant. The importance of LTP is described in Ch6 of the DoE-CWG 2025 report:

The hydrological literature has long noted the phenomenon of *Long-Term Persistence* (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2016). LTP has a formal mathematical definition, but it can be thought of as the presence of natural variations with strong autocorrelations that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records that are short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

The results when using time series > 130 years indicate that while some individual stations are calculated to have significant positive trends in extreme-event totals and occurrences, regional values do not. Thus, attributing a non-significant change in a phenomenon (increased number

of heavy precipitation events) to a specific cause (increased concentrations of GHGs as depicted in models with implausible inputs) does not follow. We conclude that the NCA5 methods and conclusions do not meet the very basic standards of scientific analysis. See Ch6 DoE-CWG 2025 for further discussion.

Diffenbaugh, N.S., D. Singh, and J.S. Mankin, 2018: Unprecedented climate events: Historical changes, aspirational targets, and national commitments. *Science Advances*, **4** (2), 3354. <https://doi.org/10.1126/sciadv.aao3354>

Kirchmeier-Young, M.C. and X. Zhang, 2020: Human influence has intensified extreme precipitation in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (24), 13308–13313. <https://doi.org/10.1073/pnas.1921628117>

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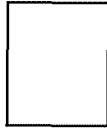
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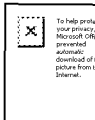
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One thing to be careful about in discussing uncertainty is that some economists (and others) use it to argue that the problem may turn out to be far worse than we expected, so we need to take even stronger precautionary measures. It's important therefore to marshal evidence specifically regarding bias (as in model warning bias) as opposed merely to uncertainty.

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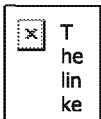
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Attachments: NCA5_00_Front Matter_3OD.pdf; NCA5_19_Economics_3OD.pdf; NCA5_02_Trends_3OD.pdf; NCA5_01_Overview_3OD.pdf; OfflineComments_NCA53OD_PublicReview.xlsm; NCA5_03_EarthSystems_3OD.pdf; NCA5_04_Water_3OD.pdf

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If we're going to criticize the peer review process (and I think we should), we've got to look at what the NASEM review said (or didn't say) about specific points and how USGCRP responded (or not) to them.

To do that, we need the report of the NASEM review and the USGCRP response (both of which I've sent around previously but also attached again here). But to match page and line references, **it would also be very helpful to have the draft NCA5 that NASEM reviewed.** That's no longer available on the web (or at least I couldn't find it), but perhaps one of you has a copy?

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On Tue, Jun 3, 2025 at 10:09 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Hi all,

I'm relaying information from a call I had last night with Audrey Barrios (senior advisor to the Secretary) and a call I had this morning with Lynne Parker (Principal Deputy Director at OSTP). Regarding authorship, this document should be written by you all (or a subset, if needed), and OSTP feels strongly that it should be published by the new Executive Director (Interim, if needed) of the USGCRP. I realize we don't know which specific person that will be yet, but that's how we should approach this work. I can share more details on the call this afternoon.

I also want to share the good news that we now have the assistance of a sharp attorney from DOE's Office of General Counsel. His name is Seth Cohen, and he comes highly recommended (litigation experience, clerkships at two different circuit courts, etc.). He can help us connect the dots between the GCRA statute, the executive order, the DOE report, and recommendations for moving forward (improving NCA 6 or whatever we're calling the next iteration). Would you all be comfortable having Seth join the call this afternoon, or should we hold off on introducing him to the team?

Best,

Travis

On Mon, Jun 2, 2025 at 10:37 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

I'm happy to adjust as needed, but 3pm ET tomorrow works for me.

Regarding the what and the why of the task, we can discuss more details on the call, but my understanding is that we should critically review NCA 5 (at whatever level of detail is feasible in a period of a couple of weeks) through the lens of the statute, the executive order, and the DOE report.

As of right now, we should write this document as a response to a request from OSTP, along the lines of the scoping memo Ross shared. There is a chance OSTP might want to claim authorship, but my hunch is that whatever you all produce next will be another group report with each of your names on it.

The next best alternative is for one of you to take the helm at GCRP and publish the next document as something of a policy statement by the new GCRP director. (That's actually my first-best approach, but I completely understand if it's too big of an ask or if certain members of this group are too Canadian.)

On Mon, Jun 2, 2025 at 9:51 PM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Sent a meeting link for 3 PM. I couldn't remember what time we agreed to and I know Roy can't be there but I thought it was around 3.

On Mon, Jun 2, 2025 at 8:24 PM Steven Koonin <steven.koonin@gmail.com> wrote:

At least some politicians are trained as lawyers and understand the concepts of evidence, proof, etc. I think we could reach them. And in the current political/culture climate, everyone is suspicious of being lied to. Worth a try, in my opinion (and experience).

Anyway, we should discuss on tomorrow's call. Do we yet have a time and video link?

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Monday, June 2, 2025 7:54 PM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Josh Loucks <loucksj14@gmail.com>

Subject: Re: an early take on NCA5 Chapter 1

well try to convince a politician of that!

Maybe we should just focus on recommendations for future NCAs

Just focusing on what they selected for the report summary isn't too helpful IMO.

I am still lost as to what we are supposed to be doing and why

On Mon, Jun 2, 2025 at 1:39 PM Steven Koonin <steven.koonin@gmail.com> wrote:

**"If I were wrong, one would be enough",
Albert Einstein upon hearing of the book
"Hundred Authors Against Einstein"**

Steven E. Koonin

On Jun 2, 2025, at 16:30, Judith Curry <curry.judith@gmail.com> wrote:

I still think it is a tough case to make that 5 scientists decide an assessment report authored by 500 scientists and reviewed by NASEM is scientifically inadequate, no matter how much cherry picking we identify. If we make the case that the NCA5 process has been politicized, then I think we have a more credible as a critique

On Mon, Jun 2, 2025 at 9:08 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I drafted the attached cover letter and outline before I saw Judy's draft. There are some obvious ways to fuse them.

I worry about getting too far out of our lane and also getting too political. Stick with the science and judge NCA5 as a scientific document informing policy – that's really all we should do.

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Monday, June 2, 2025 10:33 AM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Josh Loucks <loucksj14@gmail.com>
Subject: Re: an early take on NCA5 Chapter 1

See attached (note, this is pretty much all i can do for next 24 hours, need to be in hurricane report mode). Let me know what you think

On Sun, Jun 1, 2025 at 3:21 PM Steven Koonin <steven.koonin@gmail.com> wrote:

So how would you frame and support that more general argument?

Steven E. Koonin

On Jun 1, 2025, at 17:46, Judith Curry <curry.judith@gmail.com> wrote:

My current thinking on this is to make an argument that the NCA5 is not fit for the purpose of informing policy making: "assisting the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

I think this is the bigger issue than actual "errors" in the report -- the whole thing is based on flawed assumptions, and they're looking at the wrong things. We could find 200 errors in the report and that still wouldn't kill it.

On Sat, May 31, 2025 at 1:53 PM judith curry
<curry.judith@gmail.com> wrote:

I'm working on some introductory big picture text for our review for your consideration. Will have draft on Monday

Sent from my iPhone

On May 31, 2025, at 7:54 AM, Steven Koonin
<steven.koonin@gmail.com> wrote:

A read-through of NCA5 Chapter 1 shows some endemic issues we should flag (some of these already mentioned). Plenty of examples of each in the text.

- confusion of climate change vs changing climate (i.e., attribution of all climate changes to anthropogenic forcing)
- confusion of weather vs climate (the plural of anecdote is not evidence)
- no mention of uncertainties or significance in trends cited
- taking model results at face value (have they pruned the ensemble used?)
- no setting of scale for big numbers (e.g., dollars of climate damage relative to GDP)
- truncation of data records (ignoring the inconveniently warm 1930s)
- use of extreme, implausible scenarios (even though AR6 had already declared SSP8.5 and 7 implausible)
- no mention of benefits of climate change or how they net against disbenefits?

...

SEK

--

<~WRD0002.jpg> Judith Curry, President
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0. Front Matter

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4 Department of Commerce / National Oceanic and Atmospheric Administration

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US Global Change Research Program

Fifth National Climate Assessment

Third Order Draft: November 7, 2022

Table of Contents

0. Front Matter

1. Overview

Physical Science

2. Climate Trends

3. Earth System Processes

National Topics

4. Water

5. Energy

6. Land Cover and Land-Use Change

7. Forests

8. Ecosystems, Ecosystem Services, and Biodiversity

9. Coastal Effects

10. Oceans and Marine Resources

11. Agriculture, Food Systems, and Rural Communities

12. Built Environment, Urban Systems, and Cities

13. Transportation

14. Air Quality

15. Human Health

16. Tribes and Indigenous Peoples

17. Climate Effects on US International Interests

18. Sector Interactions, Multiple Stressors, and Complex Systems

19. Economics

20. Social Systems and Justice

Regions

21. Northeast

22. Southeast

23. US Caribbean

24. Midwest

25. Northern Great Plains

26. Southern Great Plains

27. Northwest

28. Southwest

- 29. Alaska
- 30. Hawai'i and US-Affiliated Pacific Islands

Responses

- 31. Adaptation
- 32. Mitigation

Appendices

- A1. Assessment Development Process
- A2. Information Quality
- A3. Scenarios and Datasets
- A4. Indicators

Focus On... Features

- i. Focus on Compound and Complex Events
- ii. Focus on Western Wildfires
- iii. Focus on COVID-19 and Climate Change
- iv. Focus on Risks to Supply Chains
- v. Focus on Blue Carbon

About This Report

The Global Change Research Act of 1990 (104 Stat. 3096-3104) mandates that the US Global Change Research Program (USGCRP) deliver a report to Congress and the President no less than every four years that “integrates, evaluates, and interprets the findings of the [Program]; analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.”

The Fifth National Climate Assessment (NCA5) fulfills that mandate by delivery of this assessment and provides the scientific foundation to support informed decision-making across the United States. By design, much of the development of NCA5 built upon the approaches and processes used to create the Fourth National Climate Assessment, or NCA4 (USGCRP, 2018), with a goal of continuously advancing an inclusive, diverse, and sustained process for assessing and communicating scientific knowledge on the impacts, risks, and vulnerabilities associated with a changing global climate (see App. 1).

The findings in this report are based on a comprehensive review and assessment of information sources determined to meet the standards and documentation required under the Information Quality Act and the Foundations for Evidence-Based Policymaking Act of 2018 (see App. 2), including scientific literature (e.g., peer-reviewed and gray literature, technical input reports), Indigenous knowledge, other traditional and expert knowledge, and climate projections (see Guide to the Report section below and App. 3).

NCA5 was thoroughly reviewed by Federal Government experts, external experts, and the public multiple times throughout the report development process. An expert external review was performed by an ad-hoc committee of the National Academies of Sciences, Engineering, and Medicine (2023). Additional information on the development of this Assessment can be found in Appendix 1: Assessment Development Process.

1 **Guide to the Report**

2 **Categories of Chapters and Their Scope**

3 **Overview**

4 The Overview chapter presents the major findings of the report alongside highlights drawn from
5 across NCA5. This chapter provides a synthesis of material from the underlying report chapters.

6 **Physical Science Chapters**

7 The Climate Trends and Earth Systems Processes chapters (Chs. 2 and 3) assess how climate
8 change affects physical Earth systems, with a focus on the United States, including observations
9 and projections of climate change, and how methods to understand changes in Earth systems
10 have advanced.

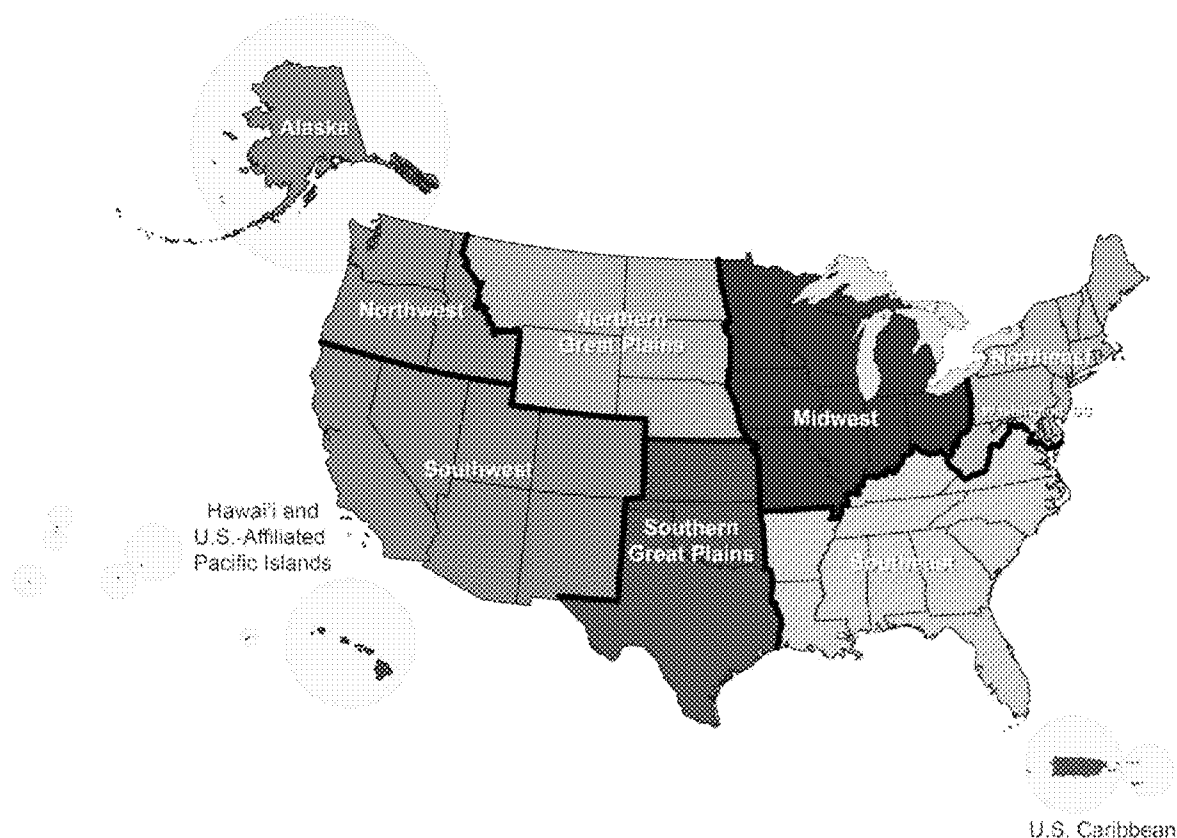
11 **National Chapters**

12 The national chapters (Chs. 4–20) summarize current and future risks related to climate change
13 and what can be done to reduce those risks for a variety of societal and economic sectors of the
14 United States. This assessment builds on the range of topics covered in NCA4 by adding two
15 new chapters: Economics and Social Systems and Justice (Chs. 19 and 20).

16 **Regional Chapters**

17 The regional chapters (Chs. 21–30) assess current and future risks posed by climate change to
18 each of the 10 NCA5 regions (Figure 1). These chapters provide detailed discussions of region-
19 specific challenges, opportunities, and success stories for managing risk.

1 **Figure 1. Map of the 10 Regions Used Throughout the Fifth National Climate Assessment**



2
3 **Response Chapters**

4 The response chapters (Adaptation, Mitigation; Chs. 31 and 32) assess the science of adapting to
5 a changing climate, emissions reductions, and other efforts that together determine US resilience
6 to climate change, including benefits, trade-offs, targets, limitations, and best practices. The
7 National Climate Assessment does not evaluate or recommend specific adaptation or mitigation
8 policies.

9 **Appendices**

10 The appendices provide additional context to the assessment, outlining the development process,
11 legal standards of scientific quality for assessing scientific information, and the climate scenarios
12 and datasets used to support author assessment. Appendix 4 explores climate change indicators,
13 with examples of observed climate changes in the US that support findings across NCA5.

14 **Focus on... Features**

15 To better address critical and timely topics with themes and implications that span the
16 Assessment, NCA5 pioneered a new feature for NCA reports: a set of five “Focus” boxes on
17 important cross-cutting issues. High-priority topics were nominated by authors during early

development of the report draft; five of these topics were approved for inclusion by the Federal Steering Committee. Authors from multiple NCA5 chapters assessed literature, coordinated cross-report discussions, and contributed text and figures to covered topics.

Structure and Format of Chapter Text

Key Messages and Traceable Accounts

Chapters are centered around Key Messages, which are conclusions based on authors' expert judgment and synthesis of the assessed information sources. Many Key Messages present findings in the context of risks to natural and/or human systems (See Overview 1.3). The text supporting each Key Message provides evidence, discusses implications, identifies intersections between systems or hazards, and presents examples of paths to greater resilience.

Evaluating confidence and likelihood is a key part of the assessment process. As in previous assessments, NCA5 uses specific terms to convey information about the degree of scientific confidence and certainty associated with important findings, observations, and projections. Unlike previous NCAs, which used a more limited list of terms, NCA5 has adopted the terms used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Mastrandrea 2011). Chapter authors use these calibrated terms to describe the **confidence** and, where appropriate, **likelihood** associated with the statements in their Key Messages (Tables 1 and 2).

- **Confidence** in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.
- **Likelihood** of a finding is based on measures of certainty expressed probabilistically; in other words, based on statistical analysis of observed or projected results or on the authors' expert judgment based on their assessment across scientific information sources.

These calibrated terms are presented in parentheses and set in *italics* after relevant phrases or sentences in the Key Messages, or at the end of a Key Message when a single likelihood/confidence assessment applies to the entire Key Message. In some cases, calibrated likelihood assessments are also included in italics in the narrative text supporting Key Messages.

Table 1. Calibrated Language for Confidence Assessment

CAPTION: NCA5 calibrated uncertainty language follows standards developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report. Source: Mastrandrea et al. 2011

Confidence Level	Definition
Very high	- Strong evidence (established theory, multiple sources, well-documented and accepted methods, etc.) - High consensus
High	- Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.) - Medium consensus
Medium	- Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) - Competing schools of thought
Low	- Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.) - Disagreement or lack of opinions among experts

Table 2. Calibrated Language for Likelihood Assessment

Likelihood Assessment	Numeric Probability of Outcome
Virtually certain	99%–100%
Very likely	90%–100%
Likely	66%–100%
As likely as not	33%–66%
Unlikely	0%–33%
Very unlikely	0%–10%
Exceptionally unlikely	0%–1%

Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the

science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

Additional information on Key Messages and Traceable Accounts can be found in the previous Front Matter for NCA4 (USGCRP 2018).

Metrics and Definitions Used Across the Report

Use of Scenarios

Climate modeling experts develop global climate projections for a range of realistic futures. These projections capture variables such as the relationship between human behavior and choices, greenhouse gas (GHG) and particulate matter emissions, Earth system processes and responses to changes in concentration of GHGs in our atmosphere and oceans, and resulting impacts, including temperature change and sea level rise. Because there are uncertainties inherent in all of these factors—especially human behavior and choices—the resulting range of projections are not predictions but instead reflect multiple potential pathways for our collective future (see Ch. 2). The scenarios do not have relative likelihoods assigned and are all plausible futures.

NCA5 authors were advised to assess the full range of scenarios available. To help communicate author findings effectively, the naming convention with simplified summary descriptions shown in Table 3 is used across the report to describe the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) used in Phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6). Scenarios other than those described in Table 3 are referred to by name. Additional information on scenarios, including sea level rise scenarios, can be found in the Overview and in Appendix 3.

1 **Table 3. Descriptive Terms for Common Scenarios Used in NCA5**

Descriptive Term	CMIP5	CMIP6	Summary
Very High Scenario	RCP8.5	SSP5-8.5	Among the scenarios described here, these reflect the highest range of carbon dioxide (CO ₂) emissions and no mitigation. Total annual global CO ₂ emissions in 2100 are quadruple 2000 emissions (RCP8.5 and SSP5-8.5). Population growth in 2100 doubles from 2000 in RCP8.5, but the SSP5-8.5 population remains relatively stable, with approximately 13% growth in 2100 from 2005. Both scenarios include fossil fuel development, but SSP5-8.5 has higher economic growth than RCP8.5.
High Scenario	RCP6.0	SSP3-7.0	These scenarios reflect high CO ₂ emissions with limited (RCP6.0) or no mitigation (SSP3-7.0). Total annual CO ₂ emissions in 2100 are more than 75% higher than in 2000 in RCP6.0, and triple that of 2000 emissions in SSP3-7.0. Compared to 2000, both scenarios include expanded fossil fuel development and population growth but slow economic growth.
Intermediate Scenario	RCP4.5	SSP2-4.5	These scenarios reflect reductions in CO ₂ emissions from current levels. Total annual CO ₂ emissions in 2100 are 46% (RCP4.5) and 67% (SSP2-4.5) less than the year 2000. Mitigation efforts include low-carbon technology (SSP2-4.5) and expanded renewable energy compared to 2000 (RCP 4.5).
Low Scenario	RCP2.6	SSP1-2.6	These scenarios reflect rapidly declining and net-negative CO ₂ emissions (with CO ₂ removal from the atmosphere exceeding human-caused emissions) by 2100. Mitigation efforts include increased renewable energy. Adaptive capacity reflects effective governance institutions, reduced inequality, and international cooperation (SSP1-2.6).
Very Low Scenario	n/a	SSP1-1.9	Among the scenarios described here, SSP1-1.9 reflects the greatest reduction in global greenhouse gas emissions and substantial CO ₂ removal from the atmosphere. Total annual CO ₂ emissions have a steeper decline than SSP1-2.6, dropping by more than 145% by 2100 compared to 2000. Mitigation efforts include a shift to nuclear and renewable energy and sustainable land use. Adaptive capacity benefits from international cooperation and sharing of technology.

2

Box 1. Global Warming Levels Measure How Much the Planet Has Warmed

A global warming level is reached when global annual warming, defined by the average temperature over multiple decades, exceeds a specified level relative to preindustrial temperatures (1850–1900 average). Although this assessment primarily reports temperatures in Fahrenheit, global warming levels are usually reported and more widely known in degrees Celsius. For example, the Paris Agreement set targets to limit global warming to “well below” 2°C (3.6°F), with a high-ambition target of 1.5°C (2.7°F).

Internal variability in the climate system means that even as the world rapidly warms, some years will be hotter and some years will be cooler than the multidecadal average. A single year in which the globe is 1.5°C (2.7°F) hotter than it was in 1850–1900 does not mean the 1.5°C global warming level has been reached. Conversely, such annual variability means that climate impacts projected to occur at a given global warming level may be experienced even before that level is reached. In addition, temperatures in different parts of the world could be warmer than the global average. A global warming level of 2°C (3.6°F) would result in regional temperatures in parts of the United States that are more than 2°C above preindustrial levels (Figure 1.16).

Global warming levels are not thresholds; they do not represent “safe” levels of warming, nor does exceeding a particular global warming level consign us to runaway impacts. Continued action to reduce emissions can avoid the worst impacts of climate change and provide valuable benefits to society and ecosystems no matter what global warming level is reached or exceeded. At regional or local scales, climate impacts, such as increased risks of extreme weather, depend on changes to underlying drivers like local temperatures and rainfall. These changes in turn depend on the level of global warming. The level of global warming depends on future emissions, which depend on human actions. This means that future projections are conditional: when or if Earth reaches a particular level of warming is largely dependent on human choices.

[END BOX 1]

Economic Estimates

When available, the dollar year associated with economic estimates in this report are provided and, where possible, converted to [2022] dollars using the US Bureau of Economic Affairs’ gross domestic product implicit price deflator. For more information, please visit: <https://bea.gov/national/index.htm>. Where discount rates have been applied, those values are specified.

Glossary of Terms

A glossary will be developed upon finalization of the report content and published concurrently with NCA5.

References

- USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.
- Mastrandrea, M.D., Mach, K.J., Plattner, G.K. et al. The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Climatic Change* 108, 675 (2011).
<https://doi.org/10.1007/s10584-011-0178-6>

19. Economics

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Date

November 7, 2022

1 Chapter Contents

2	Introduction	3
3	Key Message 19.1. Climate Change Will Affect the Economy Directly	3
4	Key Message 19.2. Markets and Budgets Will Respond to Climate Change	11
5	Box 19.1. Economic Decision-Making Under Uncertainty	15
6	Key Message 19.3. Economic Opportunities for Households, Businesses, and Institutions Will Change	15
7	Traceable Accounts	19
8	References.....	26
9		
10		

1 Introduction

2 The climate is a national asset that contributes value to diverse economic activities across the
3 United States, from agriculture, finance, and tourism to healthcare, education, and real estate.
4 Changes in the climate are expected to impose substantial new costs to the US economy and
5 adversely affect the economic opportunities of most Americans. Climate change, and the policies
6 adopted in response, are also expected to alter both the internal structure of the US economy and
7 the global economy in which the US competes. These economic consequences are projected to
8 be highly uneven across US regions, industries, and communities.

9 Climate change has *direct* and *indirect* effects on economic outcomes. Direct impacts affect
10 individuals and other basic components of the economy (e.g., buildings, crops). These direct
11 impacts may in turn cause secondary indirect impacts of climate change, which result from
12 markets, governments, and other institutions responding and adjusting to these changes. For
13 example, changes in rainfall patterns and sea level rise puts existing homes at risk of flooding
14 (direct effect) which then lowers the price of these homes, increases risks to mortgage-providing
15 businesses, and alters the kinds of flood insurance provided by the federal government to these
16 regions (indirect effects).

17 Key Message 19.1. Climate Change Will Affect the Economy Directly

18 Climate change directly impacts the economy through increases in temperature, rising sea
19 levels, and more frequent/intense weather-related extreme events (e.g., wildfires, floods,
20 hurricanes, drought), which are expected to generate substantial economic costs in many
21 sectors (*likely, high confidence*). These impacts are projected to be distributed unequally,
22 affecting certain regions, industries, and socioeconomic groups more than others (*very*
23 *likely, high confidence*). Adaptation can mitigate some impacts by reducing vulnerability
24 to climate change, but adaptation strategies vary in their effectiveness and costs (*medium*
25 *confidence*).

26 Observed Direct Impacts

27 Direct economic impacts of climate change have been observed in many economic sectors (e.g.,
28 Table 19.1, panel b). For example, more frequent extreme events and higher temperatures lead to
29 direct economic losses via infrastructure damage (Neumann et al 2021) worker injuries (Park et
30 al 2021a), and crop loss (D'Agostino and Schlenker 2016).

31 Important direct impacts of climate change also affect valuable resources that are not traded in
32 markets, such as human health or ecosystems. These *nonmarket impacts* are sometimes difficult
33 to quantify but are nonetheless economically important and represent a substantial fraction of the
34 economic burden of climate change for Americans (Table 19.1, panel c). For example, declines
35 in Americans' physical and mental health have been linked to rising temperatures, extreme
36 weather, wildfires, vector-borne diseases, food insecurity, and knowledge of the threat of climate
37 change itself (Dodgen et al. 2016; Burke et al 2018; Heutel et al. 2021; Wen and Burke, 2022;

Carleton et al. 2022). Additionally, changes in ecosystems caused by climate change have impacted food production, water resources, forestry, human health, real estate, recreation, and tourism (Lipton et al. 2018; Pershing et al. 2018).

Projected Direct Impacts

While some economic impacts of climate change are already being felt, the impacts of future changes are projected to be more significant and apparent across more sectors of the economy (e.g., Figure 19.1 and Table 19.1, panel b). Further, with every additional degree of warming, the United States overall is expected to see increasingly adverse consequences. For example, warming global temperatures by 2°F is projected to cause more than twice the economic harm induced by 1°F of warming (Hsiang et al. 2017; Dietz and Stern 2015).

As climate change advances, economic risks are projected to grow over time. For example, US weather-related disasters currently generate roughly \$150B per year in direct losses in the US (NCEI 2022) today, a cost that is projected to increase due to climate change in the near term (Swain et al. 2020; Zhang and Shindell 2021; Wing et al. 2022). Over the next few decades, climate change is projected to cause ecosystem disruptions (Walther 2010), water stress (Ortiz-Bobea et al. 2019), and agricultural losses (Schlenker and Roberts 2009). Over the coming century, the country faces relocation costs and damage to property and infrastructure due to coastal flooding (Neumann et al. 2015), major adverse impacts on ecosystem services (Dasgupta 2021), large negative impacts on economic production (Burke et al. 2015b), and a restructured investment landscape (Willner et al. 2021).

Projected economic impacts are not certain, as they depend on multiple factors that cannot be known precisely. However, the largest source of uncertainty in projected impacts is the unknown trajectory of future emissions (Hsiang and Kopp 2018), which depend on economic development, population growth, mitigation policy, and other factors (Ch. 3). Additionally, the economic uncertainty caused by climate change is itself an economic burden, since individuals are generally averse to risk (Box 19.1) (Cai and Lontzek 2019; Lemoine 2021).

Economic impacts of climate change will vary by location based on exposure to different hazards, regional patterns of climate change, and historical climate (Figure 19.1; Ch. 3). For example, locations that are hot today are generally projected to suffer greater damage because warming from 100°F to 105°F has a larger effect on human health, energy use, labor supply, and crop yields than does a warming from 60°F to 65°F (Barreca et al 2016; Carleton et al 2022; Graff Zivin and Neidell 2014; Schlenker and Roberts 2009). Population density also influences regional economic impacts of climate change, since dense populations exacerbate urban heat islands and groundwater drawdown, but improve the cost-effectiveness of some public adaptation projects, such as seawalls that protect cities (Hsiang and Narita 2012; Diaz 2016).

Cold regions may benefit from low levels of warming while temperate and hot regions are generally harmed (Hsiang et al. 2017). However, within most sectors that have been studied, more Americans are harmed than are helped by climate change (Figure 19.1b; Carleton et al.

2022, Hultgren et al. 2022, Martinich and Crimmins 2019, Rode et al. 2021, Neumann et al. 2021, Fant et al. 2021, Rode et al. 2022, Sarofim et al. 2021). As a result, estimates of nationwide impacts indicate an overall net loss in the economic well-being of American society (Figure 19.1c; e.g., Hsiang et al. 2017; Rode et al. 2021; Hultgren et al. 2022; Rode et al. 2022; Carleton et al. 2022; Martinich & Crimmins 2019).

Adaptation

Adaptation to climate change can reduce some economic impacts (Barreca et al. 2016; Diaz 2016). Natural and human systems may not be able to adapt quickly, so gradual warming is likely less harmful than rapid warming (Diaz 2016). However, some sectors are limited by how effectively impacts can be avoided through adaptation (Ch. 31; Burke and Emerick 2016; Schlenker et al. 2013; Bierbaum et al. 2013). Some adaptation strategies will require new investments, ongoing expenditures, or changes in consumption that offset or outweigh their benefits (Hsiang and Narita 2012; Deryugina & Hsiang 2017; Carleton et al. 2022). Adaptation may also face political difficulties, require behavior changes that populations are reticent to adopt (Orlove 2005), or depend on technologies that do not yet exist or are in their infancy (Wagner and Schlenker 2022). These factors make the projected timing and effectiveness of adaptations uncertain (Bierbaum et al. 2013).

Economic Vulnerability and Inequality

Economic damages from climate change are distributed unevenly across American society, often amplifying existing inequalities. Certain communities and individuals are more sensitive to climate impacts, more exposed, or lack the resources to effectively adapt to climate changes (Figure 19.2; Hoffman et al. 2020; Rode et al. 2021; Billings et al. 2022; Behrer et al. 2021; Fried 2021; Wing et al. 2022; Hsu et al. 2021; Heilmann et al. 2021; EPA 2021). For example, people with preexisting health conditions and elderly individuals may be relatively more sensitive to heat or wildfire smoke (Deryugina et al. 2019; Park et al. 2021a). Families living below the poverty line often live where climatic changes are expected to be the most economically damaging, such as the already-hot Southeast (Hsiang et al. 2017). Climate-driven relocations of Alaska Native communities have already occurred where warming is happening fastest and traditional livelihoods are no longer viable (Smith and Sattineni 2016; Albert et al. 2018). Climatic stressors have also been shown to increase segregation (Bakkensen and Ma 2020), low-income communities' reliance on social safety net programs (Deryugina 2017, Billings et al. 2022), credit systems (Roth Tran and Sheldon 2017), and income inequality (Hsiang et al. 2020).

Table 19.1. Example US Economic Impacts of Climate Extremes and Climate Change (not comprehensive)

Key: * indicates an intermediate scenario (RCP4.5) or less than or equal to 2°C warming above preindustrial levels; ** indicates a very high scenario (RCP8.5) or greater than or equal to 3°C warming; † indicates 3% discount rate.

a) Sample of current impact estimates of climate hazards on US economic outcomes				
Sector	Impact Type	Climate Hazard	Economic Estimate (US unless otherwise noted)	Source
	Crop insurance payouts	Temperature	+19% of federally subsidized payouts	Diffenbaugh et al. (2021)
	Rural outmigration	Warming-linked crop failure	+0.17% for 1% crop yield reduction	Feng et al. (2012)
	Commercial mortgage delinquency	Hurricane	+28% per 10% damage increase	Holtermans et al. (2022)
	GDP growth	Hurricane	−0.45% annual growth rate per hurricane	Strobl (2011)
	Municipal borrowing costs	Sea level rise	+23.4 bps annualized bond issuance cost	Painter (2020)
	Municipal budgets	Wildfire	+25 pp increase in likelihood of budget deficit	Liao and Kousky (2022)
	Social safety net transfers	Hurricane	+\$780–\$1,150 per capita	Deryugina (2017)
	Housing prices	Flooding	−4.6% (in 100-year floodplain)	Beltrán et al. (2018)
	Student learning	Temperature	−1% test scores per 1°F warming	Park et al. (2020)
	Property values	Sea level rise	−14.7% (1 foot rise)	Bernstein et al. (2019)
	Damage to structures and crops	Flooding	+\$199B/year	Davenport et al. (2021)
	Earnings	Wildfire smoke	−\$125B/year	Borgschulte et al. (2022)
	Work injuries	Heat (≥85°F day)	+5–15% per hot day	Park et al. (2021a)
	Wages as adult	Heat (≥90°F day)	−0.1% per hot day in-utero	Isen et al. (2017)
	Emergency department costs	Heat (≥80°F day)	+\$8,000 per 100k people	White (2017)

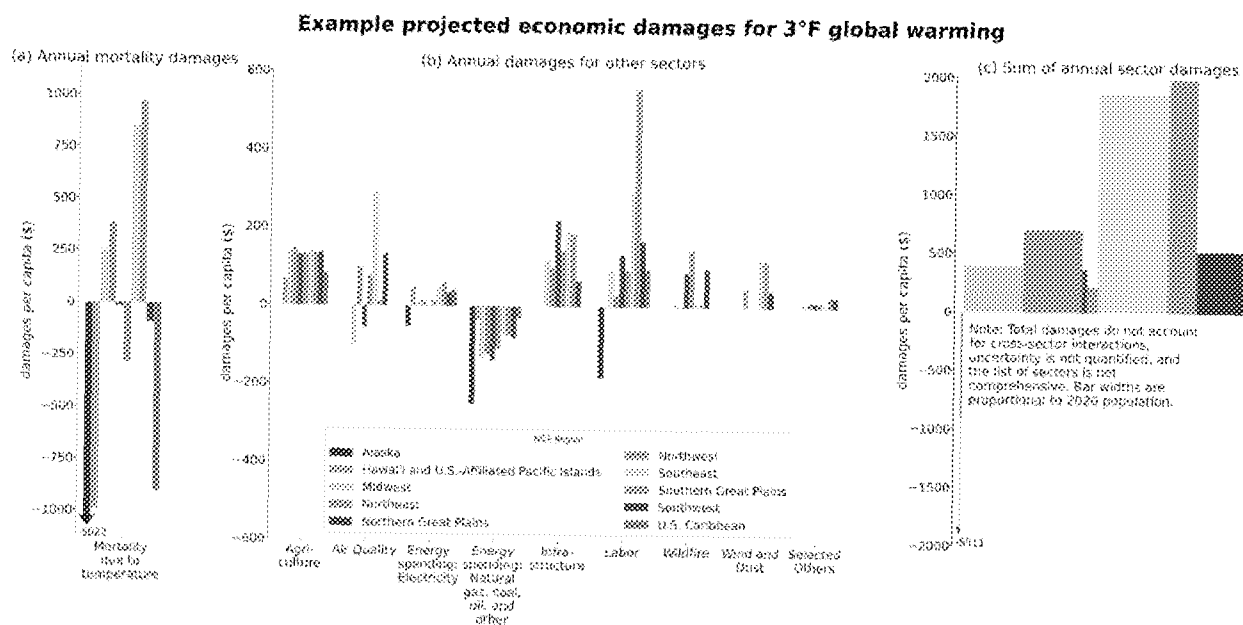
	Mortality	Heat ($\geq 90^{\circ}\text{F}$)	+0.9 deaths per 100k	Deschênes and Greenstone (2011)
	Relocating Native Alaskan communities	Warming-linked erosion	\$20–200M cost per village	USACE (2006)
b) Sample of future impact estimates of projected climate hazards on US economic outcomes				
Icons	Impact type	Climate hazard	Economic estimate (US unless otherwise noted)	Source
	Agricultural yields (6 crops)	Temperature, Moisture	–12–29%*, –20–48%** (in 2050–2100 period)	Ortiz-Bobea et al. (2019)
	Agricultural yields (3 crops)	Temperature, Precipitation	–30–46%*, –63–82%** (in 2070–2099 period)	Schlenker and Roberts (2009)
	Aggregate multi-sector impact	Temperature	–0.1–1.7% GDP loss*, 1.5–5.6% GDP loss**	Hsiang et al. (2017)
	Airline network disruption	Temperature	+25–56% recovery costs (2035, global)**	Lee et al. (2020)
	GDP growth	Temperature	–0.13%/year per 1°F	Burke et al. (2015b)
	Income	Temperature	–19.6% global GDP/capita**	Burke et al. (2015b)
	Income	Hurricanes	–29% NPV GDP loss** †	Hsiang and Jina (2014)
	Federal disaster response	Hurricanes	+\$14.6B*, \$32B** (2050 annual expenditures)	OMB (2022)
	National Flood Insurance Program	Flooding	+\$3.5B (2050), \$4.6B (2100) annual losses*	OMB (2022)
	Property tax revenue	Sea level rise	–1.4% (3 foot rise)	Shi and Varuzzo (2020)
	Public services	Temperature	+2 pp costs (2050)**	Barrage (2021)
	Coastal damages	Sea level rise	+\$419B (optimal adaptation), \$2T (no adaptation)**	Diaz (2016)
	Electricity outages	Temperature, Precipitation	+\$1.9–5.6T consumer costs**	Larsen et al. (2018)
	Flooding costs	Flooding	+61% annual losses (2050)*	FSF (2021)
	Railroad degradation/disruption	Temperature	+\$25–45B*, \$35–60B** cost from network delays	Chinowsky et al. (2019)

		Road degradation	Temperature, Precipitation	+\$80B** cost†	Neumann et al. (2015)
		Urban drainage degradation	Temperature, Precipitation	+\$20B** cost†	Neumann et al. (2015)
		Migration from Mexico to the US	Temperature, Precipitation	+1.4M*–6.7M** additional migrants	Feng et al. (2010)
		Mortality (all causes)	Wildfire	+9–20 deaths per 100k ≥65 years old (for 50% increase smoke)	Burke et al. (2021)
		Suicides	Temperature	+5,600–26,000 deaths by 2050**	Burke et al. (2018)
c) Sample of impacts that are difficult to quantify in economic terms					
		Impact type	Climate hazard	Economic estimate (US unless otherwise noted)	Source
		Happiness	n/a	n/a	n/a
		Preservation of national landmarks	n/a	n/a	n/a
		Loss of cultural heritage and resources	n/a	n/a	n/a

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2

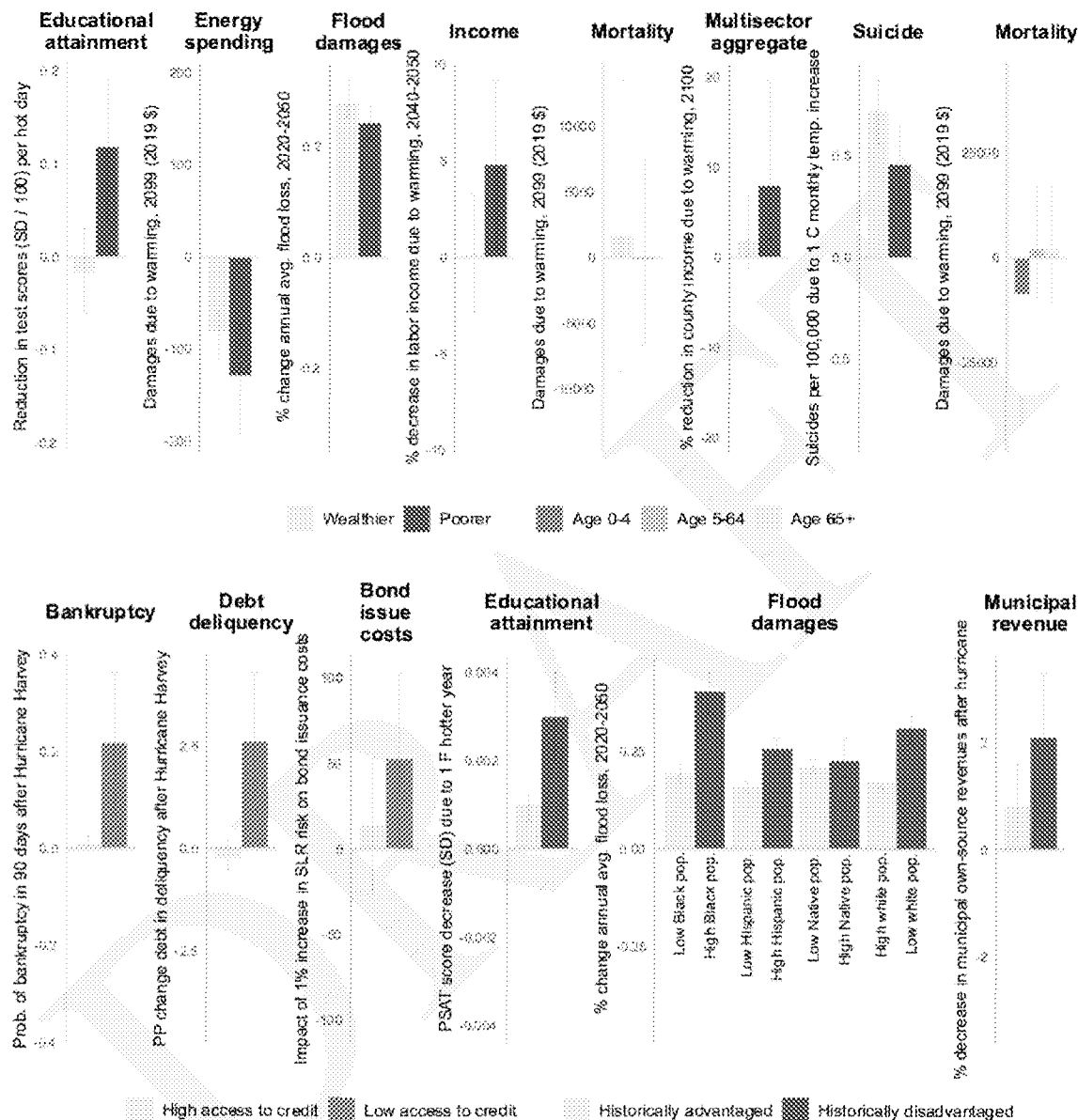
1 Figure 19.1. Example Projected Direct Impacts



CAPTION: Projected economic impacts vary across sectors and regions, with aggregate impacts resulting in net damages nationally. Shown are estimates of annual economic damages in each region for several sectors in scenarios where global surface temperature increases 3°F compared to the 1986–2005 average (positive damages indicate harm). Panels (a) and (b): per capita impacts. Panel (c): sum across sectors by region, with bar width corresponding to present-day populations (bar area is total cost). Quantified impacts differ by region and sector, but national total damages are harmful. Data sources: Carleton et al. (2022), Hultgren et al. (2022), Martinich and Crimmins (2019), Rode et al. (2021), Neumann et al. (2021), Fant et al. (2021), Rode et al. (2022), Sarofim et al. (2021).

Figure 19.2. Examples of climate damages demonstrate unequal impacts across wealth, age, access to credit, and race.

Examples of climate damages demonstrate unequal impacts across wealth, age, access to credit, and race



CAPTION: The observed and projected effects of climate extremes and climate change are often experienced differently by populations that have different wealth/income, age, access to credit, or ethnic/racial identity. Each sub-panel summarizes example findings from a single study (left to right): Park et al. (2021b), Rode et al. (2021), Wing et al. (2022), Behrer et al. (2021), Carleton et al. (2022), Hsiang et al. (2017), Burke et al. (2018), Carleton et al. (2022), Billings et al. (2022), Painter (2020), Park et al. (2020), Wing et al. (2022), Jerch et al. (2020).

Key Message 19.2. Markets and Budgets Will Respond to Climate Change

Markets are beginning to respond to current and anticipated climate changes, and stronger market responses are expected as climate change progresses (*medium confidence*). Climate risks are projected to change asset values as markets and prices adjust to reflect economic conditions that result from climate change (*very likely, high confidence*). New costs and challenges will emerge in insurance systems and public budgets that were not originally designed to respond to climate change (*high confidence*). Trade and economic growth are projected to be impacted by climate change directly and through policy responses to climate change (*likely, medium confidence*).

Markets

Markets aggregate information from many individuals and firms, generating system-level outcomes (e.g., market prices). Prices in well-functioning markets will reflect assets' exposure to future climate risks and expected adaptation costs. For example, anticipation of future flood risk has begun to reduce the prices of vulnerable properties (Figure 19.3; Bernstein et al. 2019; Bakkensen and Barrage 2021). But there are barriers that sometimes prevent market prices from adjusting to reflect climate risks (Hong et al. 2019), such as inaccurate information or incomplete understanding of relevant climate risks (Baldauf et al. 2020; Barrage and Furst 2019; Hino and Burke 2021; Keenan and Bradt 2020). Increasing awareness of climate change is expected to tighten the link between asset prices and climate risks in financial markets (Bernstein et al. 2019; Painter 2020; Gibson and Mullins 2020; Bolton and Kacperczyk 2021).

Changes in prices due to climate change can have different impacts on producers and consumers. For example, higher temperatures around the globe are expected to lead to a reduction in global production of corn, wheat, rice, and soybeans (Hultgren et al. 2022). This reduction in supply is expected to increase crop prices (Roberts and Schlenker 2013). In some cases, these higher prices could financially offset the reduction in yields for farmers, but US consumers would face the burden of the higher food prices.

Insurance markets are important for financial resilience to changing climate extremes, but insurance coverage is costly, and prices may exceed what households and businesses are willing or able to pay (Kousky and Cook 2012). As climate risks escalate and/or become more uncertain, private insurers are expected to abandon high-hazard areas, as is occurring in some wildfire and hurricane-prone locations (Kousky 2022). Uninsured consumers face greater financial distress post-disaster (Kousky 2019), and public-sector insurance programs, such as crop insurance and the National Flood Insurance Program, see increasing demand when private insurance markets contract. To account for the growing risks, fiscal costs of public insurance programs will rise (Tack et al. 2018; OMB 2022).

Stock and bond market prices generally reflect anticipated climate risks (Bansal et al. 2019), but pricing can be incomplete or distorted (Hong et al. 2019; Alok et al. 2020). Anticipated policies to curb emissions can impact stock prices of emissions-intensive companies (Bolton and

Kacperczyk 2021; Ilhan et al. 2021), and long-term bonds issued by municipalities exposed to future climate risks tend to have lower prices (Painter 2020; Goldsmith-Pinkham et al. 2021). In the absence of strong global mitigation policies, some forward-looking financial institutions are preemptively responding to potential impacts by restructuring portfolios (Krueger et al. 2020; Engle et al. 2020).

Migration, Trade, and Growth

Future climate changes are expected to increasingly affect migration patterns, although how these shifts will occur is uncertain. Historical events that have shaped migrations include extended droughts, which drove rural populations toward urban centers (Hornbeck 2012), and hurricanes, which have had persistent impacts on where people live (Deryugina et al. 2018; DeWaard et al. 2020; Meléndez and Hinojosa 2017). Projections of increased flood risks due to sea level rise (Ch. 2) are expected to displace substantial populations (Desmet et al. 2021; Depsky et al 2022; Hauer 2017). Climate-driven economic changes abroad, including reductions in crop yields, are expected to continue increasing the rate of emigration to the United States (Feng et al. 2010; Puente et al. 2016).

Global supply chains can transfer, amplify, or reduce the direct impacts of climate change (see Focus on Risks to Supply Chains). Climatic events in other countries impact trade with the United States (Jones and Olken, 2010), which in turn affects domestic markets (Ch. 17; Moore et al. 2017). Climate impacts that affect multiple countries simultaneously amplify costs due to interacting disruptions and linked trade (Dingel et al. 2019). However, geographic diversification of supply chains would allow for businesses to flexibly adjust supplies to partially reduce their exposure to climate-associated risks (Costinot et al. 2016).

High annual temperatures and tropical cyclones are associated with lower growth in gross domestic product (GDP; Burke et al. 2015b; Hsiang and Jina 2014; IMF 2017; Colacito et al. 2019), with responses from multiple industries contributing to this overall effect. For each 1°F increase in global mean surface temperature, annual US GDP growth is projected to slow roughly 0.13 percentage points (Burke et al 2015; Colacito et al 2019; IMF 2017), with larger effects for larger temperature changes. These changes in growth rates can in turn affect stock market prices and interest rates (Hong et al. 2021, Barnett et al. 2020).

Public Budgets, Healthcare, and Infrastructure

Climate change will affect public budgets at all levels of government through changes in revenues, spending, and borrowing costs (Figure 19.4; CBO 2021; Barrage 2020; Gilmore et al. 2022). For example, sea level rise, wildfires, and hurricanes can decrease incomes (Hsiang and Jina 2014; Bakkensen and Barrage 2018) and housing values (Figure 19.3; Ortega and Taspınar 2018; Gibson and Mullins 2020), and thus tax revenues (Jerch et al. 2020), while simultaneously increasing public expenditures for healthcare, income support (Deryugina 2017), disaster assistance (CBO 2016), and defense spending (DOD 2021). This combination of declining

revenue and increasing expenditures increases municipal borrowing costs (Jerch et al. 2020; Painter 2020; Goldsmith-Pinkham et al. 2021; Liao and Kousky 2022).

Climate change is expected to further increase the costs of public programs, such as crop insurance subsidies (Tack et al. 2018; Diffenbaugh et al. 2021), wildfire suppression (OMB 2016; OMB 2022; Baylis and Boomhower 2019), endangered species protection (Moore et al. 2022), and healthcare provision (Karlsson and Ziebarth 2018; Fann et al. 2018; Barrage 2021). Given these demands, achieving sustainable public budgets in a changing climate is expected to require additional revenues or other expenditure reductions (CBO 2021; Barrage 2021).

US healthcare is provided by public systems and private markets, both of which will be impacted by climate change. Extreme weather events, such as hurricanes, damage healthcare facilities and impede medical care delivery (Ebi et al. 2018; Bell et al. 2016; Mace and Sharma 2020) and create competition for healthcare services (Watts et al. 2021). The direct health impacts of climate change (Ch. 15) are expected to generate higher medical costs, raising health insurance premiums and expenditures on prevention efforts (Carleton et al. 2022; Salas et al. 2020; Walensky et al. 2017; WHO 2015).

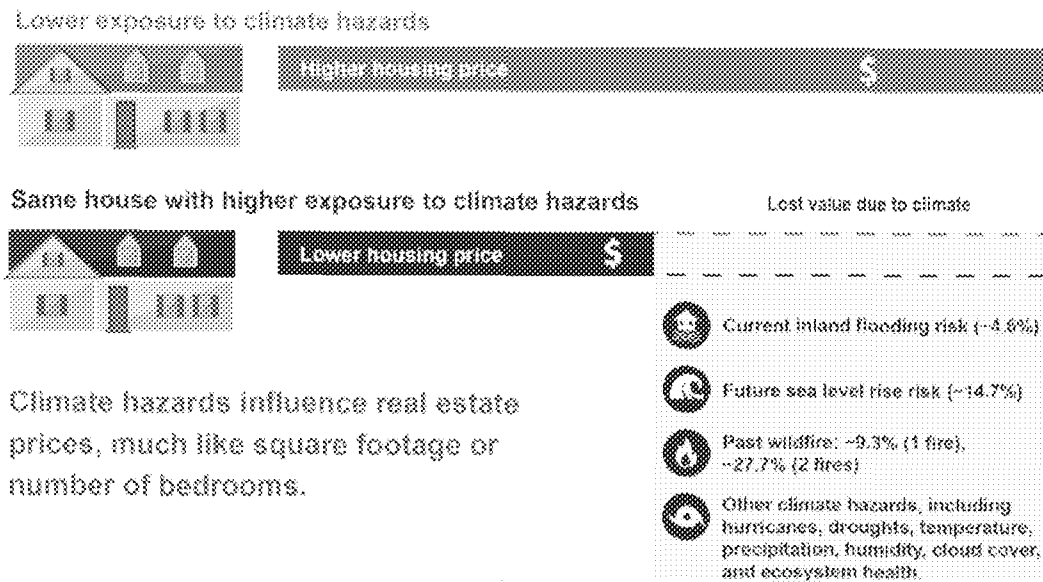
Essential infrastructure, such as water, energy, communication, and transportation systems, will increasingly be compromised by the compounding effects of climate change impacts (Chs. 4, 5, 12, and 13; see also Focus on Compound and Complex Events). Degradation or disruption of these assets, many of which are publicly owned, can have substantial repercussions on other sectors and the well-being of households (Table 19.1).

Innovation

Economic impacts of climate change will motivate some investments in innovations aimed at reducing or limiting climate damages. For example, development of low-cost air conditioning (Barreca et al. 2016) and arid-tolerant crop varieties reduced the impact of historical climate conditions (Olmstead and Rhode 2011). Future innovations may reduce costs or result in new adaptation technologies. However, some adaptation challenges have proven difficult to overcome (Roberts and Schlenker 2011), and novel adaptive technologies are sometimes costly, often limiting their accessibility to high-income communities (Rode et al. 2021). Nonetheless, strategic investments in key adaptation technologies have the potential to generate large social and private returns.

1 Figure 19.3. How Climate Hazards Impact Real Estate Prices

How Climate Hazards Impact Real Estate Prices



2

3 CAPTION: Exposure to past climate events and present/future climate risk affects real estate values for

4 properties that are otherwise the same. The market price for real estate is reduced when it is exposed to

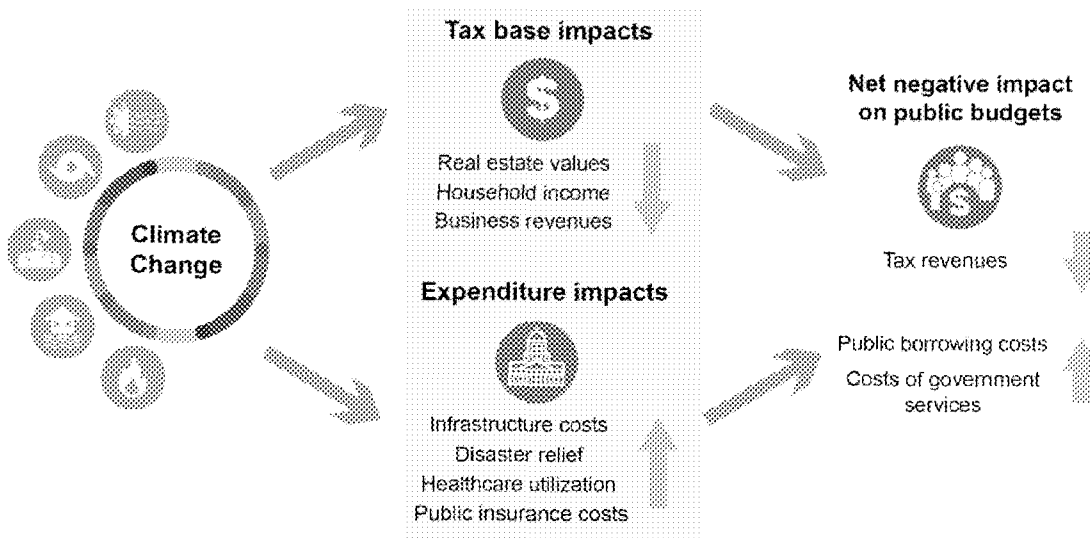
5 adverse climate extremes or risks. Shown are example estimates from studies (Beltrán et al. 2018;

6 Bernstein et al. 2019; Mueller et al. 2009).

7 Figure 19.4. Fiscal Risks from Climate Change

Fiscal Risks of Climate Change

Climate change puts pressure on public budgets.



8

CAPTION: Climate change increases demand for government services while also reducing the ability of governments to fund those services, creating new risks for the fiscal sustainability of government budgets at local, state, and federal levels. Together, this fiscal risk increases the cost to government for borrowing funds (e.g., the sale of bonds) by reducing the rating of public debt, which in turn further harms the ability of governments to fund services.

Box 19.1. Economic Decision-Making Under Uncertainty

Economists use economic and financial models to understand the potential impacts of climate change on our economy and markets. Projected outcomes depend on many uncertain factors, including technological developments, economic growth, mitigation policies, and Earth system processes. Recognizing this uncertainty is important for decision-making. Uncertainty is costly because individuals and investors dislike uncertainty; thus, society benefits from actions that can reduce this uncertainty (e.g., obtaining better information on damages). However, if uncertainty will be resolved over time, it is sometimes advantageous to “wait and see” before taking costly actions (Buurman and Babovic 2016). In other cases, some investments may be valuable specifically because they serve as a hedge against climate risks (Barnett et al, 2020). Also see Chapter 18.

[END BOX 19.1 HERE]

Key Message 19.3. Economic Opportunities for Households, Businesses, and Institutions Will Change

Climate change is projected to impose a variety of new or higher costs on most households and to impact their employment, income, and quality of life (*very likely, high confidence*). Climate change will disrupt the economic landscape that businesses face, generating new risks but also creating new opportunities (*likely, medium confidence*). Institutions and governments are expected to see existing programs used more intensively or in new ways as populations cope with climate change, generating new system-wide risks (*medium confidence*). Design, evaluation, and deployment of adaptation technologies and policies will strengthen our national preparedness for climate change (*high confidence*).

American Households

Climate change will have different economic implications for American households depending on their occupation and where they live (Colacito et al. 2019; Behrer et al. 2021). On average, climate change is projected to reduce future income gains compared to what households would achieve in the absence of climate change (Dellink et al. 2019).

Climate change is expected to impact employment by changing demand for workers, reducing worker safety (Park et al. 2021a), altering the location of available jobs (Feng et al. 2012), and

changing workplace conditions in heat-exposed jobs (Neidell et al. 2021; Rode et al 2022).

Households may also lose wealth through declines in the value of real estate (Figure 19.3).

Climate change will affect household spending (Cohen et al. 2017), for example, by changing energy use (Ch. 5; Auffhammer et al. 2017), increasing medical costs (Ch. 15; Limaye et al. 2019), elevating food prices (Ch. 11; Brown et al. 2015), raising insurance premiums, and requiring more frequent repairs and replacement of assets damaged by extreme events (NCEI 2022).

Economic prospects for children will be affected by climate change. For example, higher temperatures during in utero development negatively impact adult economic outcomes (Isen et al. 2017), while higher temperatures during childhood reduce learning (Park et al. 2020, 2021b) and lower cognitive performance (Graff Zivin et al. 2018; Park 2022).

Climate change is expected to alter the quality of life for American households (Albouy et al. 2016) by reducing life expectancy (Carleton et al. 2022), increasing crime and domestic violence (Hsiang et al 2013, Hsiang et al. 2017), damaging sleep quality (Obradovich et al. 2017), harming mental health (Obradovich et al. 2018; Burke et al. 2018), reducing happiness (Baylis 2020), and altering outdoor recreational activity (Obradovich and Fowler 2017; Wobus et al. 2017).

Adapting to climate change generates new household costs and can alter living and work arrangements. For example, homes may be retrofitted to withstand weather extremes or relocated (Sinha et al. 2018; Fan and Bakkensen 2021), and consumption patterns may change to offset harms from the climate (Deschênes and Greenstone 2011). Importantly, lower-income households may face greater risks from climate change and have fewer resources available to support the costs of adaptation (Hsiang et al. 2020).

American Businesses

Climate change is projected to reduce labor productivity and economic output across many sectors—including agriculture, finance, real estate, insurance, and services—and across many regions and states (Hsiang et al. 2017; Deryugina and Hsiang 2017; Colacito et al. 2019). Extreme weather events can reduce output for extended periods, altering GDP growth rates (IMF 2017). In projections, these effects can compound over time, generating large cumulative losses (Burke et al. 2015b; Colacito et al. 2019; Kim et al. 2021; Heutel et al. 2021).

Businesses will face increasing exposure to climate-related risks at local, national, and international levels. For example, more intense heatwaves will reduce local productivity, greater wildfire smoke will lower demand for outdoor services, and more frequent extreme events around the world will disrupt international trade, supply chains, and foreign demand for American products (Ch. 17).

Investment planning by businesses will also be affected by climate change. For example, the location of firm capital investments may change in response to more frequent weather disasters

(Kousky et al. 2006) and regional adaptation efforts, such as seawalls, may be funded via corporate taxes or impact the rate-of-return on other investments (Hsiang & Jina 2015). Investment strategies for climate-resilient technologies and the total cost of insurance for capital investments (Ch. 31) are both expected to be impacted by climate change. In addition, uncertainty in impacts and the effectiveness of adaptation may delay investment schedules (see Box 19.1).

Managing climate-related business risks can draw on established practices for general risk management. For example, in response to pressure from regulators and investors, disclosure of a business's climate-related risks and management strategies are increasingly needed. To support this, risk assessment tools for quantifying physical risks are currently being developed in public and private sectors (Swart 2019; TCFD 2017).

Governments and Institutions

Local, regional, national, and international governments and institutions (e.g., universities, professional associations, nongovernmental organizations) play a major role in facilitating individual and coordinated adaptation responses and enabling cost-effective decisions. Federal agencies are required to develop adaptation plans (Executive Order 14008), while some states, local governments, and tribal governments are developing plans varying in scope and complexity (Chs. 31 and 32).

Governments at all levels would benefit from preparing for the fiscal impacts of climate change, considering impacts on revenues, expenditure requirements (e.g., healthcare, income support), and borrowing costs (CBO 2021; Liao and Kousky 2022; Barrage 2021). Reducing the overall societal cost of extreme events may be possible through investments in public infrastructure, healthcare, and community resilience programs (Frimpong et al. 2020; Mullins and White 2020; Garg 2020) and through public support for private adaptation, including fiscal support (Fried 2021), updated building codes (Ch. 12; Simmons et al. 2018; FEMA 2020; Baylis and Boomhower 2022), and better climate-risk information and disclosures (Lee 2021). Such public programs also have the potential to reduce the inequitable impacts of climate change (Kousky 2018; Hsiang et al. 2020). Financial preparedness by households and public entities, such as through insurance take-up (Painter 2020; Gallagher and Hartley 2017), improved credit (Painter 2020; Billings et al. 2022), and specialized financial instruments (Phan and Schwartzman 2021), can shift risk or reduce losses. However, public insurance support or provision can decrease incentives for private adaptation (Annan and Schlenker 2015; Fried 2021).

It is sometimes important for governments or institutions to quantify the overall economic impact of climate changes caused by certain current activities, for example, in the analyses of whether benefits of a new climate policy are larger than its costs. A succinct summary description of costs widely used in economic analyses is the “social cost of greenhouse gases,” defined as the cumulative global economic harm to society caused by additional greenhouse gas emissions (Figure 19.5; NASEM 2017). Institutions and governments considering the economic

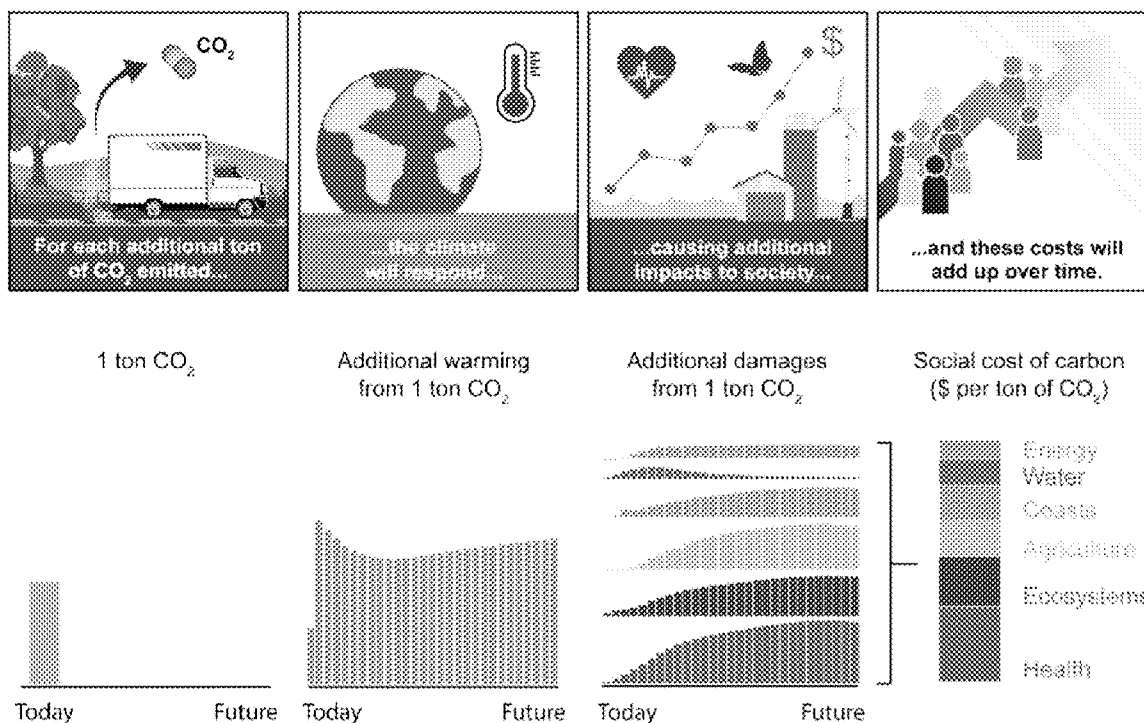
consequences of emissions may find estimates of this measure helpful, although they should familiarize themselves with some of the analytical and ethical judgements used in its construction. In 2010, twelve agencies from the federal government developed a process for estimating the social cost of greenhouse gases and periodically updating it based on scientific advances (IWG 2021). The current interim estimate used by the federal government is \$51, \$1,500, and \$18,000 per ton of carbon dioxide, methane, and nitrous oxide, respectively (2020 emissions, 3% discount rate; IWG 2021).

There is growing concern that climate change could pose a systemic risk to financial stability (Brunetti et al. 2021; US Commodity Futures Trading Commission 2020; Financial Stability Oversight Council 2021; Phan 2021; Hansen 2022; Jung et al. 2021). Negative economic impacts on even a limited number of entities could, in principle, lead to cascading effects, causing wider failure in the financial system. For example, declines in property values due to climate change could adversely affect mortgage markets and financial institutions' balance sheets, potentially leading to financial distress, especially if climate risks are imperfectly priced or if they are concentrated at government-sponsored enterprises (Ouazad and Kahn 2022; Brunetti et al. 2021; US Commodity Futures Trading Commission 2020; Phan 2021, 2022; Bakkensen et al 2022). While more research is needed to understand these systemic effects, some underlying risks can be managed. For example, the risk of future asset price corrections, driven by misalignment between current prices and the expected effects of climate change (Hong et al. 2019; Bernstein et al. 2019; Baldauf et al. 2020; Bakkensen and Barrage 2021; Murfin and Spiegel 2020; Gibson and Mullins 2020), can be mitigated through communication and disclosure of climate risks to market actors (Gibson and Mullins 2020; Lee 2021).

Climate change has the potential to undermine conditions that support overall societal stability, which may threaten economic stability, and vice versa. Global warming has the potential to impede the ability of institutions and governmental organizations to function smoothly (Obradovich et al. 2018; Heyes and Saberian 2019) and increase political turnover (Obradovich 2017), and it is directly implicated in increasing rates of violence and unrest (Ranson 2014; Burke et al. 2015a). Some extreme events have triggered widespread mortgage delinquency (Du and Zhao 2020), insurer default (Kunreuther and Michel-Kerjan 2011), breakdown in support for leaders (Healy and Malhotra, 2010), and the migration of large populations domestically (Cattaneo et al. 2019; Acosta et al. 2020) and internationally (Missirian and Schlenker 2017; Cai et al. 2016)—which in turn impacted downstream markets (Belasen & Polachek 2008; Deryugina et al. 2018). Coping with these destabilizing effects may require investment in systems that buffer and stabilize economic and social conditions, such as social safety nets, insurance, defense spending, and confidence-building mechanisms (Deryugina 2017; Kousky et al. 2017; DOD 2021).

1 Figure 19.5. The Social Cost of Greenhouse Gases

Modeling the social cost of carbon dioxide



CAPTION: The social cost of greenhouse gases is a monetary estimate of the total economic value resulting from emissions of 1 ton of carbon dioxide (CO₂), or an alternative greenhouse gas, today (NASEM 2017, IWG 2021). This value allows society to compare the economic benefits of mitigating emissions against the costs of doing so.

Traceable Accounts

Process Description

The chapter lead author was identified in July 2021, and the author team was recruited in July–August of 2021. Authors were selected based on their expertise on broad topics critical to the economic impacts of climate change on the US economy. Technical contributors were recruited by January of 2022, identified based on their expertise on specific types of impact. Effort was made to ensure that both the author team and technical contributors represented a diverse range of backgrounds from across the country, including representation from academia, the private sector, nongovernmental organizations, and economic units of the Federal Government. Of the invitations sent, two potential authors declined—one due to new administrative duties at their home institution and one who chose to participate in another chapter of the National Climate Assessment—and one potential technical contributor declined due to concerns about the possible

negative impact on their professional research output. The Economics chapter hosted an online engagement workshop on January 31, 2022. The authors also considered other outreach with stakeholders and inputs provided in the public call for technical material, and incorporated the available scientific literature to write the chapter.

Discussion within the team, along with consideration of a systematic review of available scientific literature developed by the Technical Contributors, led to the development of three Key Messages. Because previous National Climate Assessments did not have a chapter on Economics, the team considered all scientific material that was not previously discussed in other chapters of prior assessments. Based on scoping by the National Climate Assessment Steering Committee, the Economics chapter focused on the economic impact of climate change on the US economy and did not consider economic aspects of potential mitigation policies, which was out of scope. Particular attention was paid to the emerging scientific understanding of inequity of impacts across the country, which informed all Key Messages. Figures were developed by the author team, with support from Technical Contributors, to highlight key concepts that support the Key Messages. Entries to the tables of example impacts were selected, based on an evaluation of their topical importance and breadth of coverage, from a much larger database of more than 300 entries collected by the Author Team and Technical Contributors in their review of scientific evidence.

Key Message 19.1. Climate Change Will Affect the Economy Directly

Description of Evidence Base

There is mounting evidence of climate change impacts on economic costs. This literature requires multidisciplinary expertise bridging the physical sciences and economics. Broadly, the approaches to estimating climate impacts include biophysical process models, structural economic models, statistical or empirical methods, and hybrid approaches, with each methodology having strengths and weaknesses. A common finding in the above literature (Schlenker and Roberts 2009; Auffhammer and Aroonruengsawat 2011; Graff Zivin and Neidell 2014; Barreca et al 2016) is that moderate temperature and/or rainfall are usually beneficial, while cold and heat spells negatively affect a sector, as do droughts and floods. Given this relationship with an optimum at moderate temperature/rainfall levels, impacts will vary by 1) the baseline climate and 2) the predicted change and 3) the vulnerability to such changes. First, colder places might actually benefit from warming as colder temperatures are replaced with moderate ones. Most of the above papers find an asymmetric relationship with regard to temperature, where being too hot is worse than being too cold. Hence, the effect of an increase in extreme heat is the dominant driver for most places in the US leading to a net loss. Second, predicted climate change is not uniform around the world, and higher latitudes (further removed from the equator) are predicted to see higher warming. Third, vulnerabilities vary significantly across groups, for example, the sensitivity to extreme heat is larger in cold places (Butler and

Hybers 2013) and poorer places tend have higher mortality effects of hotter temperatures (Carleton et al 2020)

The literature addresses adaptation either by assessing it directly or assuming results are inclusive of adaptive responses (Carleton et al. 2022). Examples of directly assessing adaptation include study of the development and penetration of air conditioning to reduce future temperature-related mortality (Barreca et al. 2016), the use of drought-tolerant crop varieties to limit the impact of some historical climate events (Olmstead & Rhode 2011), and the building of seawalls and nourishment of beaches to protect infrastructure and ecosystems from sea level rise (Diaz, 2016). Research often assumes optimal adaptation, but some studies have considered partial adaptation to be more reflective of observed reality (Lorie et al. 2020).

Major Uncertainties

A major source of uncertainty in estimates of climate change's economic impacts is representing complex interactions among physical, natural, and social systems. There are a number of critiques of the existing literature, but also many important advances. Major uncertainties arise around unmeasured impacts, damages due to nongradual weather or climate changes, interactions between regions and sectors, risk aversion, distributional effects, and accounting for adaptation processes and costs. Improving the robustness of economic impact estimates is an active area of research. Recent reports (NASEM 2017) and others evaluate the current state of scientific knowledge, better characterize key uncertainties, and improve transparency.

One point of uncertainty regards the shape or functional form of the climate damage function. While many empirical studies have found that the increase in global, regional, and sectoral damages as the climate warms can be approximated by a quadratic damage function (Hsiang et al. 2017; Howard and Sterner 2017; Sarofim et al. 2021), disagreement remains, particularly for higher temperatures. Several studies (Nordhaus 2019; Dietz et al. 2021; Kemp et al. 2022; see also Dietz et al. 2022 reply to comments by Keen et al. 2022) argue that the damage function should become substantially steeper at higher levels of warming.

Damage projections in many sectors do not fully account for likely reductions in future vulnerabilities, for example as has been observed in the past for temperature-related mortality (Barreca et al. 2016; Carleton et al. 2022). More study of how the relationship between sensitivity of impact sectors (such as agricultural yields, mortality, or energy consumption) to weather fluctuations and income has changed over time may improve this area of research, as it remains unknown whether confounding factors influence cross-sectional comparisons sometimes used to estimate patterns of adaptation.

Description of Confidence and Likelihood

There is *high confidence* that climate change will directly affect the economy and that impacts will be unevenly distributed because numerous papers document these results across many sectors, and papers that study the same outcomes generally agree on the sign and magnitude of

these impacts. Many findings are replicated by distinct author teams. Furthermore, insights from biology and physiology, derived from experimental and/or observational data, often support econometric findings. However, the changes in the primary drivers of some of these impacts have complex patterns (e.g., wildfires, floods, drought, hurricanes), while some regions or impact categories may see benefits from warming (e.g., avoided heating expenditures). Therefore, taken together, the finding regarding the substantial cost of these impacts is only deemed *likely*. This same complexity supports the finding of unequal distribution of impacts, so that finding is deemed *very likely*. This unequal distribution is a direct consequence of the different baseline climate (known by looking at current climate), different amount of warming (consistent finding in climate models), and different underlying vulnerabilities due to social determinants such as sensitivity and adaptive capacity. The finding that currently warm places are more negatively impacted by additional warming than colder places is widely supported and garners *high confidence*. Similarly, the fact that vulnerabilities vary by income and education has also been repeatedly observed. Neither point is controversial in the literature.

Given the breadth of approaches to analyzing adaptation, the literature is more varied in conclusions drawn regarding the level of risk that adaptation is likely to ameliorate, the cost of the adaptation actions, and the likelihood that these adaptation actions will actually be implemented. Future innovations may reduce the costs of existing adaptation technologies, or they may result in entirely new technologies. However, some adaptation challenges have proven difficult to overcome (Roberts and Schlenker 2011), and ultimately, success is uncertain and there do not exist established approaches to forecasting these innovations. Furthermore, public efforts to adapt to the climate sometimes have perverse outcomes and it is unclear that similar efforts will be dramatically more successful in the future. For example, in the United States, public provision of both crop insurance subsidies and disaster aid have been estimated to increase vulnerability to extreme weather (Annan and Schlenker 2015; Fried 2021). For all of these reasons, there is only *medium confidence* in findings regarding adaptation.

Key Message 19.2. Markets and Budgets Will Respond to Climate Change

Description of Evidence Base

Multiple lines of evidence, including theoretical and empirical analyses, demonstrate effects of anticipated climate risks on financial markets. For example, anticipated increases in flood risks due to sea level rise reduce the prices of vulnerable coastal properties (Bakkensen and Barrage 2021; Bernstein et al. 2019; Baldauf et al. 2020) and the prices of long-term bonds issued by vulnerable municipalities (Painter 2020; Goldsmith-Pinkham et al. 2021). These effects have increased over time, coinciding with increasing investor attention to climate change (Bernstein et al. 2019; Goldsmith-Pinkham et al. 2021; Giglio et al. 2021). Emerging evidence demonstrates potential sources of market inefficiencies due to government policies. For example, existing securitization programs by government-sponsored enterprises, such as Fannie Mae and Freddie

Mac, unintentionally encourages banks to issue mortgage loans to properties that are exposed to hurricane risks (Ouazad and Kahn 2022).

For public budgets, adverse fiscal impacts of more frequent and intense natural disasters are well established. Hurricanes increase public expenditure requirements for healthcare and other programs (Deryugina 2017; CBO 2016), decrease local tax revenues (Jerch et al. 2020), and increase municipal borrowing costs (Jerch et al. 2020). Wildfires have similarly been shown to increase public expenditures on fire suppression and other programs (Baylis and Boomhower 2022; OMB 2016; Liao and Kousky 2022; Barrage 2021; Miller et al. 2017; Alman et al. 2016; Gan et al. 2017). Evidence on natural disaster impacts on tax revenues is mixed across event types and levels of government (e.g., Liao and Kousky 2022, find positive local revenue impacts of wildfires in California, due to a unique state law that freezes property assessments for taxes until a sale; and Miao et al. (2018) fail to detect significant tax revenue impacts of disasters at the state level). Certain climate impacts may also have partial fiscal benefits, although the evidence is less strong (e.g., Martinich and Crimmins 2017; Barrage 2021). However, the same evidence base also suggests negative *net* impacts. For example, Liao and Kousky (2022) estimate large increases in the probability of municipal deficits as a result of wildfire events. Conceptually, disasters such as hurricanes and flooding, can also have adverse impacts on tax bases, such as through negative effects on economic growth (Strobl 2011; Hsiang and Jina 2014; Bakkensen and Barrage 2022) and property values (Hallstrom and Smith 2005; Ortega and Taşpınar 2018; Gibson and Mullins 2020). Finally, the literature documents other fiscal climate costs such as from infrastructure (Martinich and Crimmins 2017), the Endangered Species Act, (Moore et al. 2022), and increasing exposure to flood risk in the balance sheets of financial institutions (Bakkensen et al. 2022) and government-sponsored enterprises (Ouazad and Kahn 2022).

For insurance, private markets are important for financial resilience and climate adaptation, but these markets may be stressed by climate change. For example, it is well understood that, as climate risks grow, it is increasingly difficult for insurers to offer policies at rates that both reflect risks accurately and that consumers are able and willing to pay, leading to a growing disaster insurance gap (e.g., Issler et al. 2019; Netusil et al. 2021; Kousky 2022). Current risk and thus insurance pricing systems may become outdated with changing climatic conditions (e.g., GAO 2021). Evidence suggests that households and businesses with insurance tend to recover better and faster from disasters (reviewed in Kousky 2019, also Billings et al. 2022).

There is growing evidence that global supply chains can transfer, amplify, or reduce the direct impacts of climate change. Multiple studies have documented that climate events in other countries impact trade with the United States, which in turn affects US domestic market conditions (Jones and Olken 2010; Moore et al. 2017; Roberts and Schlenker 2013). A smaller number of studies have identified ways that climate change also causes physical events that impact entire regions, generating costs that can be amplified by production networks (Acemoglu et al. 2012; Dingel et al. 2019). It is theoretically well understood that flexible supply chain networks can also enable adaptation to climate change by enabling geographic diversification

(Costinot et al. 2016), although there is not a large body of empirical evidence to demonstrate how this occurs in practice.

Major Uncertainties

There is considerable uncertainty regarding the estimated effects of climate risk exposure on asset values. For example, estimates of the effect of sea level rise risk on coastal real estate prices vary from as large as –20% (Bernstein et al 2019) to zero (Murfin and Spiegel 2020). There is also substantial uncertainty about the extent of exposure of financial institutions to climate-related risks (Jung et al. 2021). More research would be needed to understand how climate risks affect prices and quantities in debt markets, especially the mortgage market and mortgage-backed security market, and to understand the potential sources of market inefficiencies in pricing and allocating climate risks.

For public budgets, while evidence suggests that many public program costs may be affected by climate change, many of these impacts remain unquantified (e.g., law enforcement and military expenditure changes due to potential increases in crime and international conflict, respectively). Research is also limited on interactions between different climate impacts, such as on migration and fiscal outcomes. For both public budgets and insurance markets, policy uncertainty compounds the difficulty in projecting climate impacts.

Description of Confidence and Likelihood

There is evidence of market responses to climate change, although the literature on this topic varies in terms of estimates of the magnitude and timing of the response, which leads to a determination of *medium confidence* for this finding. However, climate risk factors are *very likely* to be an important driver of asset values in the future. There is already a significant body research documenting the capitalization of weather-related risks into the prices of durable assets (real estate, stocks, long-term bonds, etc.), including a growing number of papers finding a reflection of the assets' exposure to future climate risks (e.g., sea level rise, flooding, wildfires, or anticipated carbon policies), leading to a determination that this linkage is *very likely*, although the magnitude varies and estimates of how price changes will unfold over time are uncertain. The literature on this is robust enough to warrant *high confidence*. There is *high confidence* that climate change will stress insurance systems and public budgets that were designed before global warming. There is *medium confidence* that trade and economic growth are both *likely* to be impacted by climate changes, and by the policy responses designed to mitigate climate change.

Key Message 19.3. Economic Opportunities for Households, Businesses, and Institutions Will Change

Description of Evidence Base

Substantial literature supports the conclusion that climate change will impose new costs on households and businesses (Hsiang et al. 2017; Colacito et al. 2019; Behrer et al. 2021). In particular, research has focused on income (Hsiang et al. 2017; Colacito et al. 2019; Burke et al. 2015b; Nordhaus 2017; Dellink et al. 2019; Kompas et al. 2018; Roson and Sartori 2016), employment (Feng et al. 2012, Graff Zivin and Neidell 2014; Neidell et al. 2021, Park et al. 2021a), and changes in real estate value (Bernstein et al. 2019; Baldauf et al. 2020; Bakkensen and Barrage 2021; Hino and Burke 2021; Murfin and Spiegel 2020). Businesses face increased costs in a variety of areas. These costs include: reduced productivity due to heatwaves; lower demand for outdoor activity at more distant locations due to wildfire smoke; supply chain disruption due to hydrologic extreme events (e.g., tropical cyclones in Asia, where semiconductor manufacturing is concentrated); property damage and business interruption losses from weather-related extremes (Collier et al. 2020a, 2020b); and reduced foreign demand for American products (D'Agostino and Schlenker 2016; Behrer, A. P., et al. 2021; Costinot et al. 2016).

Literature also supports the fact that it is possible to reduce the societal cost of extreme climate-related events through investments in hazard mitigation (Davlasheridze et al. 2017; Fried 2021; Neumann et al. 2021), including updated building codes (Kousky and Michel-Kerjan 2017; Simmons et al. 2018; FEMA 2020; Wagner 2022; Baylis and Boomhower 2021) and public provision of better climate-risk information, such as flood risk disclosures (Pope 2008; Lee 2021). Research has also shown that existing and new programs and activities associated with public and private institutions will need to play a role in helping to mitigate and adapt to climate change (CBO 2021; Deryugina 2017; Miao et al. 2018; Painter 2020; Liao and Kousky 2022; Jerch et al. 2020; Barrage 2021; OMB 2016). Household financial preparedness and specialized financial instruments (Phan and Schwartzman 2021) can also play a role in reducing losses from climate extremes. While insurance against natural disasters can financially protect households and businesses, these markets are themselves being stressed by climate change, with much natural disaster coverage now offered through fully or quasi-public programs (Kousky 2022). It remains the case that those most in need of the financial protection of insurance are least able to afford it. There is strong evidence that public healthcare and social support programs can mitigate climate vulnerability in certain settings (Mullins and White 2020; Garg 2020).

Major Uncertainties and Research Gaps

It is challenging to anticipate all the ways that household, businesses, and institutions will change in the face of a wide range of climate impacts: continued research on observed and projected

responses to climate changes will refine and improve quantitative estimates of the implications of these changes. In particular, systemic risks have proven more difficult to conceptualize and model, and while they could be extremely costly, have received less research attention. We also have limited understanding of nonlinearities in the costs or threshold effects that may materialize in both natural and human systems. Public programs can potentially mitigate the inequality of climate impacts in important ways, but more research would be required to identify cost effective and scalable strategies (Kousky et al. 2018). There are also uncertainties regarding how to target healthcare and other social support programs to achieve the largest net benefits.

Description of Confidence and Likelihood

There is a large literature base and high agreement regarding the variety of new or higher costs, leading to the finding of *very likely* and *high confidence* for this statement. There is less literature available characterizing the effect of disruption on the economic landscape, and while new risks predominate, there is a subset of papers that discuss the potential for new opportunities that business can take advantage of: this leads to the *likely* and *medium confidence* finding. Similarly, there is less literature regarding the response of institutions to changing climate conditions leading to a *medium confidence* finding. There is extensive literature and a high level of agreement that private and public investments in adaptation and mitigation can reduce household and business costs, leading to the assessment of *high confidence*.

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- 7

2. Climate Trends

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1 Chapter Contents

2	Introduction	3
3	Key Message 2.1. Climate Is Changing, and Scientists Understand Why	4
4	Key Message 2.2. The Risk of Extreme Events Is Increasing	14
5	Key Message 2.3. The Future Is in Our Hands	18
6	Traceable Accounts	31
7	References.....	38

8

9

Introduction

Human activities are changing climate. The evidence for warming across multiple aspects of the Earth system is incontrovertible, and the science is unequivocal that increases in atmospheric greenhouse gases are driving many observed trends and changes (Ch. 3). There are more greenhouse gases in the atmosphere because humans have burned and continue to burn fossil fuels to generate energy (Canadell et al. 2021). Greenhouse gases are also produced by industrial processes, deforestation, and agricultural practices (Canadell et al. 2021). Atmospheric concentrations of the primary greenhouse gas produced by human activities, carbon dioxide (CO₂), have increased by over 47% since 1850, while levels of other greenhouse gases like methane (CH₄) and nitrous oxide (N₂O) continue to rise (Canadell et al. 2021). As a result, the planet is on average about 2°F (1.1°C) warmer than it was in the late 1800s (Hansen et al. 2010; Rohde and Hausfather 2020; Vose et al. 2021; Morice et al. 2021). No natural processes known to science could have caused this long-term temperature trend. The only credible explanation for the observed warming is human activities (Ch. 3).

This has consequences for the United States, which over the past fifty years has been warming about 68% faster than the planet as a whole. This changing climate increases the risk of some forms of extreme weather, with a cascade of effects. In the 1980s, the country experienced on average one (inflation-adjusted) billion-dollar weather disaster every four months. Now, there is one on average every three weeks (NOAA NCEI 2022). Advances in attribution science (Ch. 3) increase our confidence that many of these events are linked to climate change, and we can now even quantify how much more frequent and/or severe a specific event has become because of human-caused warming. Some events, such as the torrential rainfall from Hurricane Harvey that caused large-scale flooding in Texas in 2017, were made more likely and more intense by human-caused climate change (van Oldenborgh et al. 2018). Others, such as the record-breaking 2021 June heatwave in the Pacific Northwest, would have been virtually impossible without it (Philip et al. 2021).

Climate-fueled extreme weather also has consequences for the health and well-being of the Nation's people (Ch. 15) and the land and ocean ecosystems on which we depend (Chs. 8 and 10). The Pacific Northwest heatwave resulted in more than 229 heat-related fatalities, widespread die-offs of shellfish and other marine organisms, crop damage, and other impacts on the region's ecosystems (NOAA NCEI 2022; Raymond et al. 2022). Extreme heat is currently the leading cause of summertime death and illness in the United States and was responsible for more than 700 deaths per year between 2004 and 2018 (Vaidyanathan et al. 2020), with some estimates of heat-related mortality closer to 1,300 deaths annually (Sarofim et al. 2016; Shindell et al. 2020). Western wildfires, made more severe by climate change (Focus on Western Wildfires), have destroyed towns and contributed to an increase in the frequency and persistence of widespread harmful air quality days across the US West (Ch. 14 Kalashnikov et al. 2022a). These impacts are not felt equally across society: socio-economic and demographic factors make certain groups vulnerable. For example, Americans over 65 are several times more likely to die

of heat-related cardiovascular disease than younger people. Black Americans die from heat-related diseases at a rate twice that of the general population (EPA 2022b). The spatial patterns of climate impacts partially reflect current and past policy choices: low-income neighborhoods, including those historically affected by redlining or other discriminatory policies, can be as much as 12°F hotter during heatwaves than wealthier neighborhoods (Hoffman 2020).

These extreme events occur against a changing backdrop as climate change pushes aspects of the Earth system into a “new normal.” Long-term warming trends are associated with shifts in other aspects of the climate system: for example, both ongoing drought in the Western US (Williams et al. 2020) and heavier precipitation and increased flood risk in the East (Kunkel et al. 2020) are linked to rising temperatures (Ch. 3). These trends are projected to continue in the near term even if future greenhouse gas emissions fall substantially. Put simply, across the country, communities are built for a climate that no longer exists. We have no choice but to adapt to a changing climate.

Key Message 2.1. Climate Is Changing, and Scientists Understand Why

It is *virtually certain* that human activities have increased atmospheric levels of carbon dioxide and other greenhouse gases (*very high confidence*). Global average temperature has risen in response, with even more warming experienced in the continental United States and Alaska (*virtually certain, very high confidence*). Long-term changes have been observed in many other aspects of the climate system (*very high confidence*). The Earth system is complex and interconnected, which means changes in faraway regions also affect the United States (*high confidence*).

Table 2.1. Concentrations of Greenhouse Gases That Cause Global Warming Are Increasing

Caption: Humans are increasing atmospheric concentrations of planet-warming gases, including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Since 1850, CO₂ concentrations have increased by more than 47%, N₂O by 23%, and CH₄ by more than 156% (Canadell et al. 2021). While CH₄ and N₂O are more powerful greenhouse gases, CO₂ is considered the primary greenhouse gas emitted by human activities; in 2020, it accounted for almost 80% of US greenhouse gas emissions (EPA 2021).

Greenhouse Gas	1850 Concentration	2020 Concentration	Lifetime	Sources	Sinks
Carbon dioxide	280 parts per million (ppm; Etheridge et al. 1996)	412 ppm (Dlugokencky et al. 2018).	see below*	Fossil fuels, land-use change	Land and ocean

Methane	700 parts per billion (ppb; Kirschke et al. 2013)	1,878 ppb (Saunois et al. 2020)	9.1 ± 0.09 years	Fossil fuel production and use, agriculture and waste, landfills, biomass/fuel burning, natural sources such as wetlands	Chemical loss and soil uptake
Nitrous oxide	275 ppb	333 parts ppb	116 ± 9 years (Prather et al. 2015)	Agriculture (Jia et al. 2019), fossil fuel combustion, biomass and biofuel burning, wastewater, natural sources such as soils, rivers, estuaries and coastal oceans (Tian et al. 2020)	Stratospheric destruction

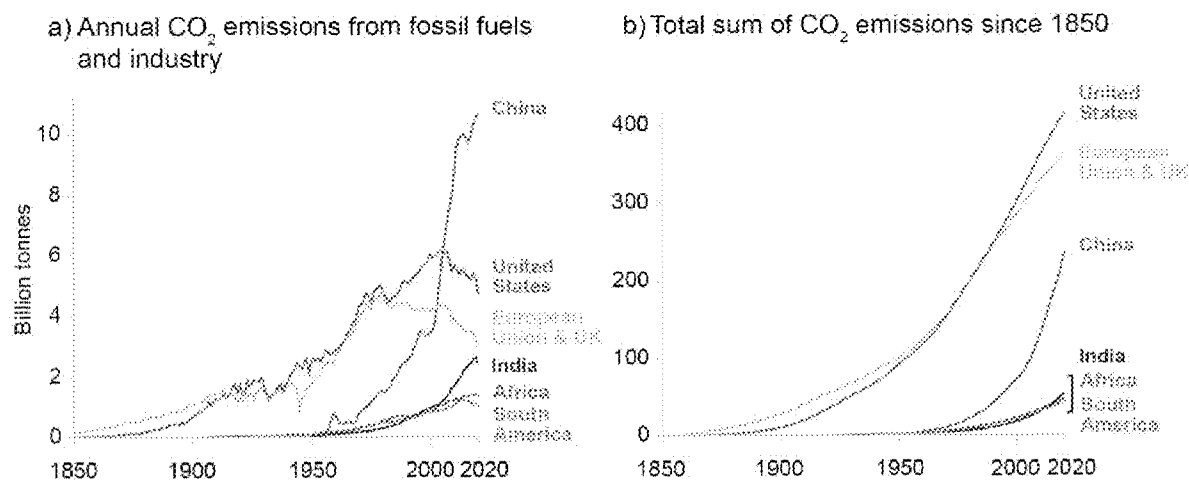
* Carbon dioxide's lifetime cannot be represented with a single value since CO₂ is not destroyed over time but instead moves among different compartments in the ocean-atmosphere-land system. The rate at which this transfer happens can vary from months to thousands of years, thus making it unrealistic to provide a single value, unlike CH₄ and N₂O. Also see <https://www.epa.gov/climate-indicators/greenhouse-gases>.

The United States Has Contributed More to Climate Change Than Any Other Country

Currently, China emits more CO₂ per year than any other country (Figure 2.1a). However, the United States has contributed more to climate change. This is because the CO₂ not removed by natural sinks remains in the atmosphere for thousands of years, and while US emissions are now lower than China's and falling, past emissions continue to affect the climate. The US is responsible for more than a quarter of the excess CO₂ added to the atmosphere since 1850

(Figure 2.1.b). While it is currently the second largest emitter, between 1960 and 2020 the United States added 21% of cumulative CO₂ emissions, while China added 17%. The long lifetime of atmospheric CO₂ is also why the pandemic-related reduction in greenhouse gas emissions, which fell 7% between 2019 and 2020 (Le Quéré et al. 2020; Liu et al. 2020; Friedlingstein et al. 2022), had no measurable impact on atmospheric CO₂ concentrations and little effect on global temperatures (Lovenduski et al. 2021).

Figure 2.1. GHG Emissions from the US and Other Sources



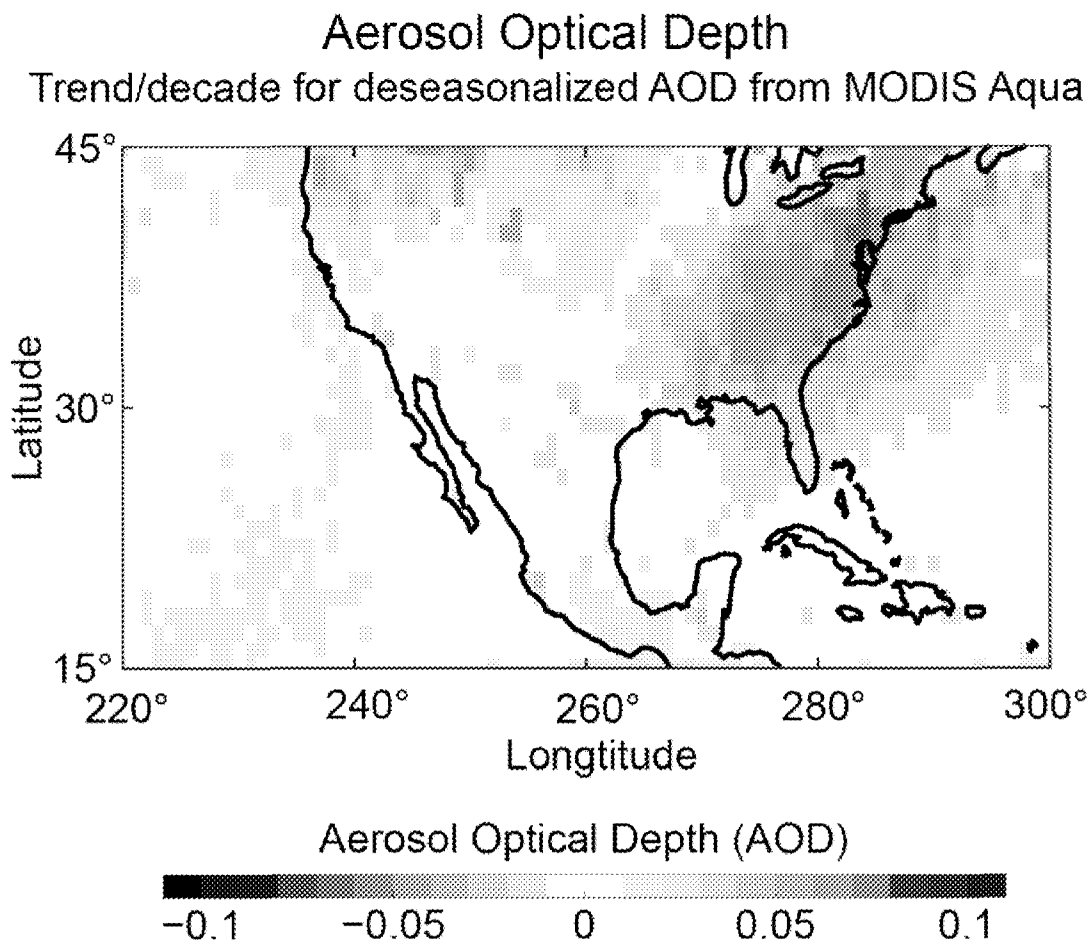
CAPTION: (a) Annual carbon dioxide (CO₂) emissions of selected world regions. China is currently the world's largest emitter of CO₂, having surpassed the United States in 2006. (b) Cumulative carbon dioxide emissions of selected world regions. Historical emissions from the United States are responsible for 27% of the excess CO₂ now in the atmosphere, a larger proportion than for any other country. Data sources: Global Carbon Project, Our World in Data. Figure source: Columbia University

Greenhouse Gases Are Not the Only Air Pollutants that Affect the Climate

Burning fossil fuels and other human activities produce small airborne particles known as aerosols. Aerosol emissions are an important constituent of air pollution, which is responsible for more excess deaths in the United States than murders and car accidents combined (Thakrar 2020). Aerosols also affect climate: directly, by blocking sunlight, and indirectly, through effects on clouds (Ch. 3). Increased global aerosol emissions have partially counteracted the warming caused by greenhouse gases, but compared to CO₂ aerosols are more localized and shorter-lived. Aerosol emissions in the United States have dramatically decreased since the passage of the Clean Air Act and subsequent pollution control legislation (Figure 2.2), and global emissions of aerosols have shifted to South and East Asia. COVID-19-related shutdowns (see Focus on COVID-19) decreased aerosol emissions and reduced their cooling effect, leading to a small and temporary global warming effect estimated at 0.05°F (Gettelman et al. 2021). In addition, other

factors such as land-surface changes including agricultural expansion and intensification and urbanization have contributed to more localized temperature effects (Mueller et al. 2016).

Figure 2.2. Aerosol Optical Depth



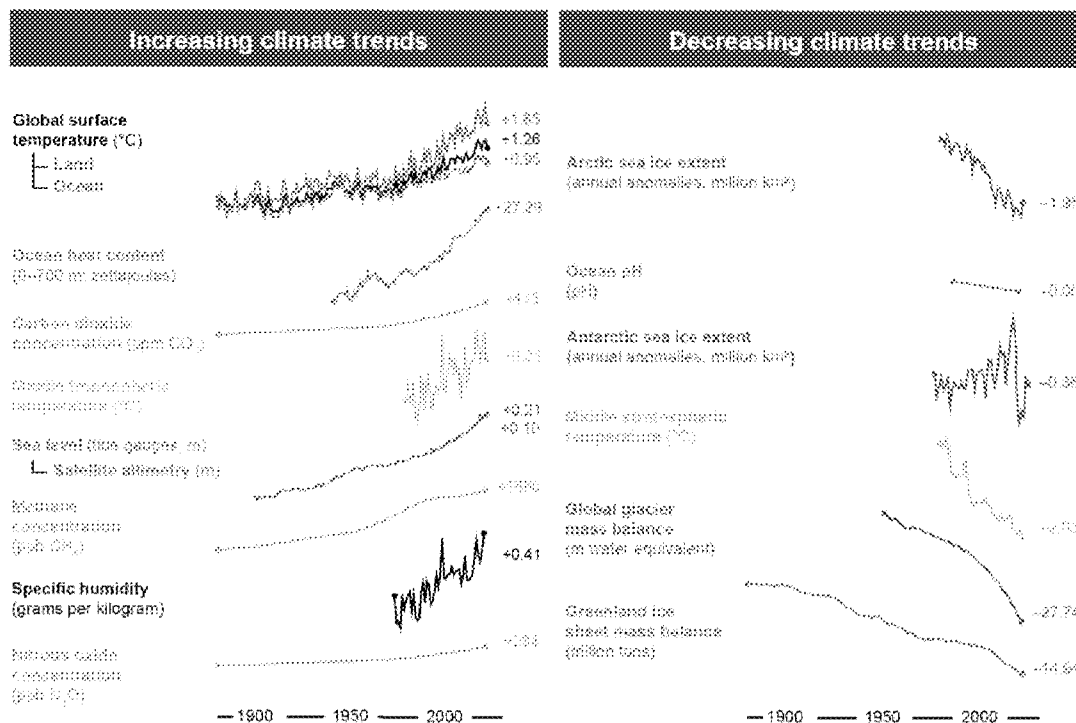
CAPTION: Aerosol pollution over and downwind of the eastern US has decreased significantly in recent decades. This figure shows the trend from July 2002 to December 2021 in aerosol optical depth, a measure of the total amount of aerosol in the atmosphere derived from satellite observations. Data source: Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) observations from July 2002 to December 2021. Figure source: NASA Langley Research Center.

Climate Change Is Already Here

Global average temperatures over the past decade (2012–2021) were close to 2°F warmer than the preindustrial period (1850–1899) (Hansen et al. 2010; Vose et al. 2021; Morice et al. 2021; Rohde and Hausfather 2020). This warming has been accompanied by other large-scale changes: loss of glaciers, ice sheet mass, and sea ice; ocean warming, acidification, and deoxygenation; increases in ocean heat content and marine heatwaves; increases in atmospheric humidity; shifting rainfall patterns and more frequent heavy precipitation; seasonal shifts including shorter

winters and earlier spring and summer seasons; and changes in the biosphere (such as land and ocean species shifting poleward). Global average sea levels over the past decade were also higher than in the preindustrial period by between 7 and 9.5 inches (18 and 24 cm), with more than half of this rise occurring since 1980 (Dangendorf et al. 2017; Nerem et al. 2018; Frederikse et al. 2020). A subset of notable global climate trends is shown in Figure 2.3.

Figure 2.3. Evidence for Climate Change Across Multiple Variables



CAPTION: Climate change is apparent in many different aspects of the Earth system. Observations of the atmosphere, land, oceans, and ice sheets show rapid changes since the mid-1800s. Source: NOAA NCEI and CISESS NC.

The Changes We Face Are Unprecedented in Human History

Paleoclimate evidence indicates that the last time the atmospheric CO₂ concentrations were as high as today was during the mid-Pliocene (approximately 3.2 million years ago; Bartoli et al. 2011; Martínez-Botí et al. 2015). Evidence from multiple proxy-based reconstructions of the past indicates that the rate of increase of global surface temperatures observed over the last 50 years exceeded any previous 50-year period in at least the past 2,000 years (Emile-Geay et al. 2017).

The Climate in the United States Is Changing

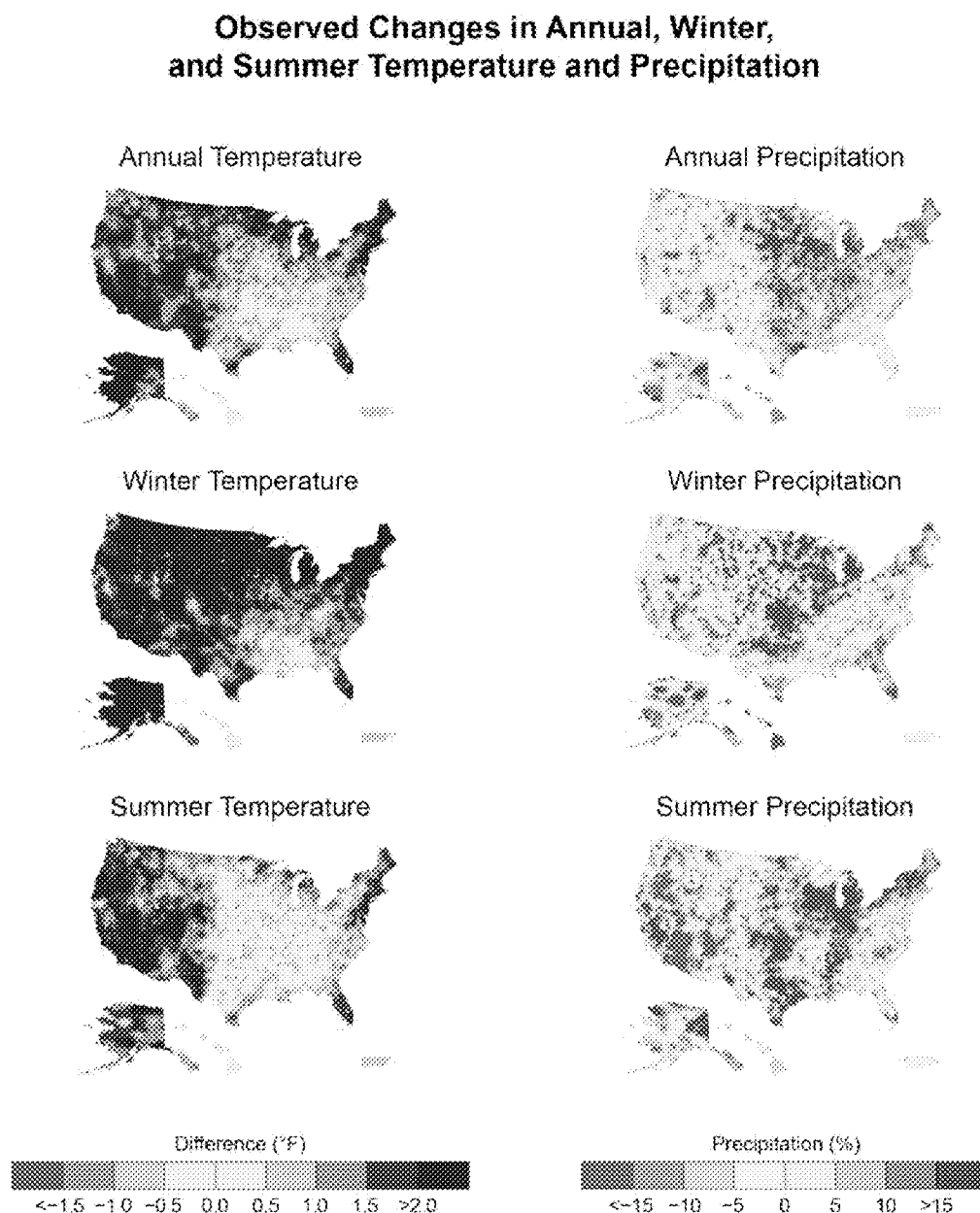
The US Is Warming Faster Than the Global Average

The United States has been warming faster than the global average since the early 1970s. Temperatures in the contiguous United States (CONUS) have risen by 2.5°F since 1970, compared to a global temperature rise of around 1.6°F over the same period. This reflects a broader global pattern in which land is warming faster than the ocean, higher latitudes are warming faster than lower latitudes, and the Arctic is warming fastest of all (Rantanen et al. 2022). There are substantial seasonal and regional variations in temperature trends across the US. Winter is warming nearly twice as fast as summer in many northern states (Figure. 2.4). Annual average temperatures in several western states are more than 2°F warmer than they were in the first half of the twentieth century, while eastern states have warmed less than 1°F. These regional differences are most pronounced in the summer: seasonal temperatures in parts of the central and eastern US have actually decreased due to a combination of natural climate variability, agricultural intensification, and aerosol pollution (Figure 2.4; Ch. 3).

The Characteristics of Precipitation Are Changing

Long-term precipitation trends differ considerably by region and season (Figure 2.4). Annual precipitation increased 5%–15% in several states in the Midwest, Great Plains, and the Northeast and decreased 10%–15% in the Southwest relative to the 1901–1960 average. These changes are not uniformly distributed throughout the year (Fig 2.4). For instance, parts of the Pacific Northwest received 10%–15% less precipitation in the summer and fall but experienced over 15% more precipitation in the spring. In contrast, in most of the Southwest precipitation was more than 15% below average during summer, fall, and spring, and 10%–15% above average in the winter (Goss et al. 2020; Zhang et al. 2021). The Northeast and Midwest have experienced wetting in all seasons, while the Southeast has experienced the strongest wetting in the fall, with drying in large areas during the summer and spring seasons (Bishop et al. 2019).

1 **Figure 2.4. Observed Changes in Annual, Winter, and Summer Temperature and Precipitation**

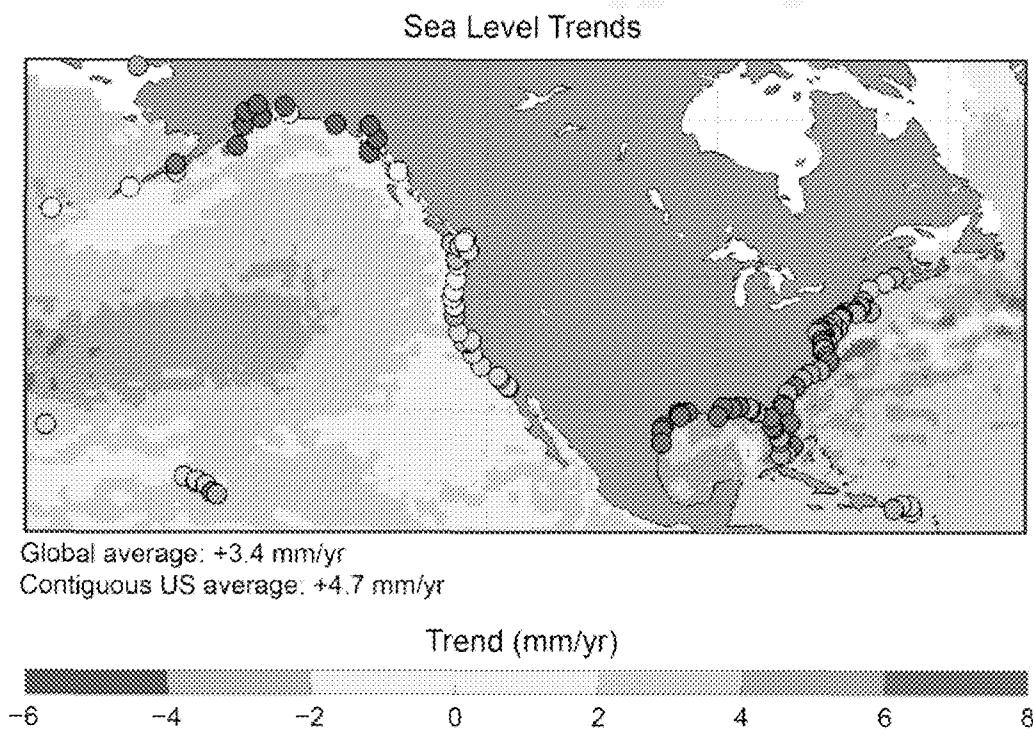


2
3 CAPTION: Much of the United States has warmed and experienced changes in precipitation. Changes
4 shown are the difference between the average for the present day (1992–2021) and the average for the
5 first half of the last century (1901–1960 for the contiguous United States [CONUS], Hawai'i, and Puerto
6 Rico; 1925–1960 for Alaska). Temperature and precipitation estimates for CONUS and Alaska are derived
7 from the nClimGrid dataset (Vose et al. 2014, 2017). For Hawai'i and Puerto Rico, temperature estimates
8 are derived from NOAA GlobalTemp (Vose et al. 2021), and precipitation estimates are derived from the
9 Global Precipitation Climatology Center dataset (Becker et al. 2013). Source: NOAA NCEI and CISS NC.

Sea Levels Along the Continental US Are Rising More than the Global Average

Over the past century, sea level along the continental US coastline has risen by about 11 inches on average, which is considerably greater than the global average sea level rise of 7 inches (Frederikse et al. 2020). Over the past three decades, the rate of sea level rise in the continental United States has been accelerating (Figure 2.5; App. 4), a change which has also been observed globally (Dangendorf et al. 2019). Within the US, rates of sea level rise vary spatially, with the highest rates observed along the Gulf and Mid-Atlantic coasts, lowest rates in the Pacific Northwest, and sea level fall in Southeast Alaska. Many processes contribute to these regional differences, with land subsidence being important in driving very high rates of relative sea level rise (sea surface relative to land surface height) along the Gulf Coast, gravitational effects from glacier loss driving lower rates in Alaska, and changes in Atlantic Ocean circulation driving higher rates over sea level rise along the mid-Atlantic Coast (Harvey et al. 2021). In some regions, small changes in local sea level have led to significant changes in the frequency of high tide flooding events due to the increased proximity of baseline water level to local flood thresholds. Correspondingly, changes in average sea level have led to a doubling of disruptive high tide flooding in the continental United States over the past few decades (Sweet et al. 2018). In some cities, such as Miami Beach, Florida, locally higher rates of sea level rise have led to a fourfold increase in the frequency of disruptive high tide flooding events over the last 20 years (Wdowinski et al. 2016).

Figure 2.5. Sea Level Rise Map



CAPTION: Satellite and tide gauge data show trends in sea level rise from 1993–2020. Sea levels are not rising uniformly across the US coast. Adapted from Sweet et al. 2022.

Oceans Are Changing

The oceans are warming off all US coasts, but not all areas are warming at the same rate (Pershing et al. 2015; Smale et al. 2019). Surface waters off Alaska and the Northeast are warming faster than in most other regions (Jewett and Romanou 2017). Oxygen minimum zones (areas of the deeper ocean where oxygen levels are naturally low) have expanded in volume since 1970, particularly in Alaskan waters, with negative consequences for fisheries (IPCC 2019; Hicke et al 2022; Breitburg et al. 2018; Ch. 10). Dead zones (areas in the coastal ocean where oxygen levels seasonally drop, sometimes causing massive die-offs of marine life) are happening in more places around the country, with climate change one of many factors contributing to their expansion (Breitburg et al. 2018; CENR 2010). Acidification, caused by rising levels of atmospheric CO₂ being absorbed by the ocean, has changed the carbonate chemistry of US offshore and coastal waters at variable rates, with impacts to marine life (Barton et al. 2015). Acidification in offshore and open ocean waters tracks the global average reduction (Canadell et al. 2021), but changes in US coastal waters depend on regional upwelling conditions, acidifying contributions from land, and nutrient and freshwater inputs (Xu et al. 2020; Gomez et al. 2020).

Sea and Lake Ice Is Decreasing

Sea ice has continued a consistent retreat in Alaska coastal seas over the last several decades (Mahoney et al. 2014; IPCC 2019; Ch. 29; App. 4). In 2018, sea ice in the Bering Sea of Alaska reached a record low at less than half the average winter extent since 1979 (Thoman et al. 2020). Throughout North America and the Arctic, lake ice area and seasonal duration have also undergone notable decreases during the satellite era (Dauginis and Brown 2021; Imrit and Sharma 2021; Ch. 24).

Changes Outside National Borders Affect the United States

Warming in the Tropics Affects Weather Throughout the United States

Warming in the tropics affects the states and territories located there, but tropical warming has consequences even for faraway parts of the country. Observed changes in atmospheric circulation are shifting the distribution of precipitation throughout the tropics and subtropics (IPCC 2021a) and are increasingly thought to extend tropical cyclone tracks farther into the midlatitudes (Sharmila and Walsh 2018), especially in the West Pacific basin. Tropical cyclone activity in the West Pacific has been linked to an intensifying effect on the El Niño–Southern Oscillation (ENSO; Lian et al. 2019; Wang and Li 2022; Wang et al. 2019). ENSO itself has tended toward more extreme events since the 1950s (Cai et al. 2021), heavily influencing temperature and precipitation patterns in several US regions (e.g. Murphy et al. 2014; Cook et al. 2018; Jong et al. 2021) as well as the development of hurricanes in the Atlantic and Eastern and Central Pacific (Lin et al. 2020). In addition, the tropics are a key source of moisture for atmospheric rivers and tropical storms that bring precipitation to much of the country. As the tropics warm, the subsequent increase in moisture is therefore also intensifying precipitation

1 associated with these systems across the western and eastern United States (e.g., Hu and
2 Dominguez 2019; Algarra et al. 2020).

3 **Ice Sheet Changes in Greenland and Antarctica Translate to US Sea Level Rise**

4 The pattern of mass loss from glaciers and ice sheets outside the United States also has an
5 important influence on the spatial pattern of sea level rise along US coasts, as ice losses in
6 Antarctica lead to more sea level increase along the US East Coast than equivalent ice losses in
7 Greenland, due to gravitational changes associated with the redistribution of mass on the Earth's
8 surface (Larour et al. 2017; Mitrovica et al. 2018). Constraints on sea level during past warm
9 periods in Earth's prehistory are now directly being used to calibrate projections of the upper
10 bound of future sea level rise (Gilford et al. 2020; DeConto et al. 2021). The closest analog for
11 current rates of sea level rise, and those that may be attained in the next century, are past warm
12 periods when the Greenland and Antarctic ice sheets were considerably smaller than their present
13 state and global mean sea level was several meters higher (Dutton et al. 2015). Ultimately, the
14 onset of enhanced flooding frequency in coastal areas depends not only on the local trend in sea
15 level but also low-frequency tidal cycles (Thompson et al. 2021) and remote climatic variability
16 (e.g., the Pacific Decadal Oscillation, El Niño–Southern Oscillation, and North Atlantic
17 Oscillation; Hamlington et al. 2021).

18 **Arctic Changes Affect Weather in the Midlatitudes**

19 The Arctic is warming faster than much of the world, and Arctic sea ice is declining rapidly as a
20 consequence. There is growing evidence from modeling studies and observations that these
21 changes in the Arctic are affecting the atmospheric circulation and extreme weather across the
22 United States. In summer, the temperature contrast between the Arctic and the midlatitudes has
23 decreased, weakening the midlatitude jet stream and making certain weather regimes more
24 persistent. This has led to more persistent hot and dry extremes over parts of North America
25 (e.g., Coumou et al. 2018; Francis et al. 2018; Kornhuber et al. 2021). However, the connection
26 between Arctic warming and winter weather is still under debate. In winter, the influence of
27 natural climate variability and the lack of consistency between observations and modeling-based
28 studies make it difficult to connect changes occurring in the Arctic and winter severe weather
29 (Blackport et al. 2019; Cohen et al. 2020). However, some recent studies that combined
30 observations and numerical modeling suggest that Arctic warming results in increasing
31 disruptions of the stratospheric polar vortex that cause cold air from the Arctic to spill down over
32 the United States, as seen in recent severe winter weather events such as the February 2021 cold
33 snap that affected large parts of the country (Cohen et al. 2018, 2021). Notably, this Arctic air,
34 while still cold in absolute terms, is warmer than it used to be four decades ago.

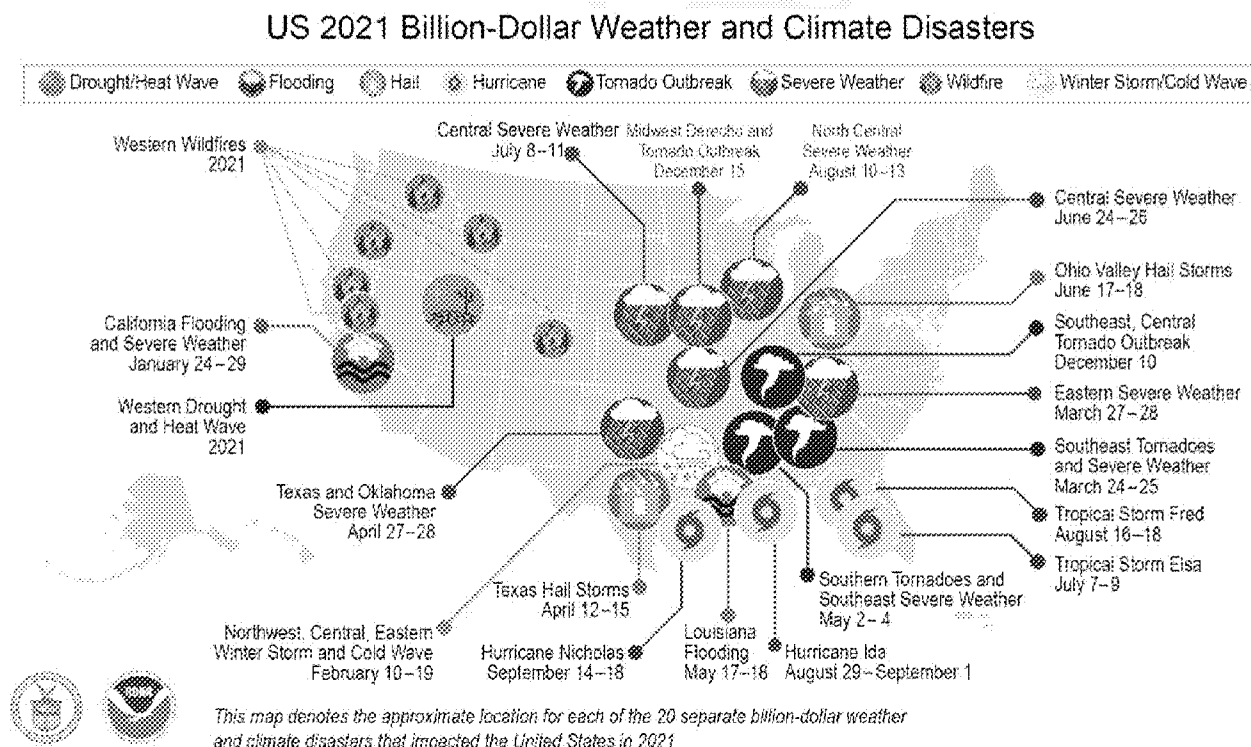
Key Message 2.2. The Risk of Extreme Events Is Increasing

Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events (*very high confidence*). Heatwaves have become more common since the 1980s (*very high confidence*). Drought risk has been increasing in the Southwest over the past century (*very high confidence*) and decreasing elsewhere (*medium confidence*). Rainfall has become more extreme in recent decades, especially east of the Rockies (*very high confidence*). Hurricanes are intensifying more rapidly (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*). More frequent and larger wildfires have been burning in the West in the past few decades due to a combination of climate factors and policy (*high confidence*).

Climate Change Is Not Just a Problem for Future Generations, It's a Problem for Us Today

The number and cost of weather-related disasters has increased dramatically over the past four decades, in part due to the increasing frequency and severity of extreme events. In 2021 alone, the United States experienced 20 weather and climate disasters with damages exceeding \$1 billion (Figure 2.6; App. 4). There is increasing confidence that changes in some extreme events are driven by human-caused climate change (Ch. 3).

Figure 2.6. Billion-Dollar Weather and Climate Disasters in 2021



CAPTION: In 2021, the US experienced more than 20 billion-dollar disasters. Source: NOAA.

Heatwaves Have Become More Common

Since the 1980s, unusually high temperatures have become more frequent (Rogers et al. 2021) and unusually cold temperatures less frequent in the western United States. Changes are more varied across the central and eastern regions due to the summer cooling trend in the region (Ch 3). Low nighttime temperatures are critical for allowing human (and animal) bodies and the built environment to cool down. However, nighttime temperatures are rising faster than daytime temperatures, and the extent of CONUS experiencing unusually warm summer nights is growing at a faster rate than the extent experiencing unusually warm daytime temperatures in summer (van Oldenborgh et al. 2019). In summer 2020, over 50% of CONUS experienced unusually hot (ranking in the highest 10%) nighttime temperature extremes, compared to about 35% experiencing unusually hot daytime high temperatures (EPA 2022a). Despite some recent damaging cold events, overall cold extremes are becoming less frequent and milder (van Oldenborgh et al. 2019; Smith and Sheridan 2020).

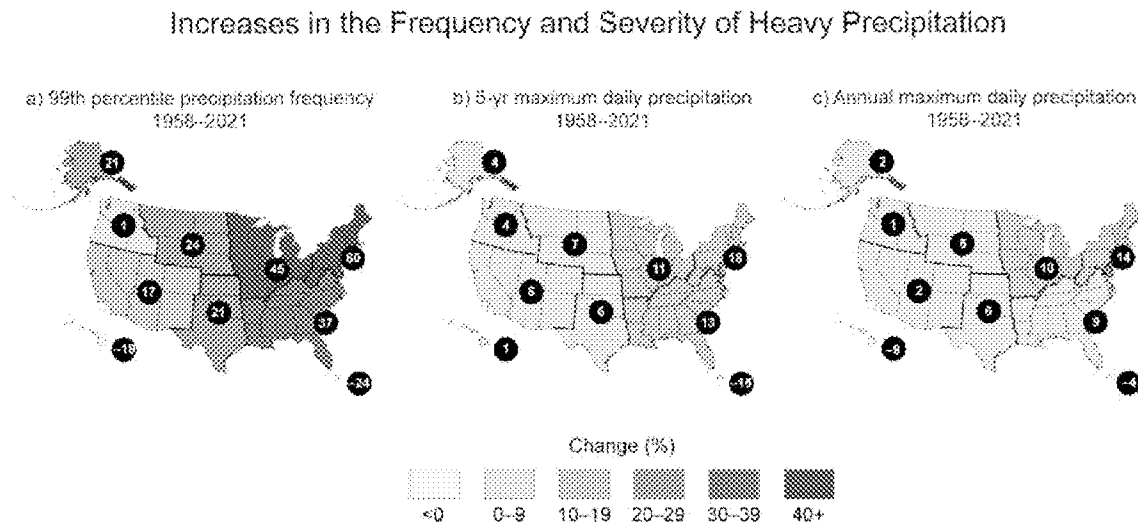
The impacts of extreme high temperatures are more severe if such conditions persist for several days. Overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting, and co-occur more frequently (e.g., Lyon and Barnston 2017; Keellings and Moradkhani 2020; Rogers et al. 2022). In addition, humidity makes warm temperatures feel hotter. Higher temperatures combined with rising humidity due to the increased atmospheric moisture content are contributing to increases in humid heat, conditions that limit the ability of the human body to naturally cool down and are associated with reduced productivity and adverse health impacts (Ch. 15). Levels of humid heat are typically higher over the eastern than the western US, and these humid heat extremes are increasing around the Gulf and south Atlantic coasts (Rogers et al. 2021). Even the ocean is experiencing extreme heats: marine heatwaves—prolonged periods of discrete (from days to several months) anomalously high sea surface temperatures—have now been documented in every US marine system (Ch. 10; Cooley et al. 2022).

Rainfall Is Becoming More Extreme and Flood Risk Is Increasing

Over the past several decades, there has been an upward trend in heavy precipitation across the contiguous US (Figure 2.7, Kunkel et al. 2020). This increase is driven largely by more frequent precipitation extremes with relatively smaller changes in their intensity. The increase is evident across a broad range of event durations (from 1 to 30 days) and return intervals (1 to 20 years), particularly east of the Rocky Mountains (Dunn et al. 2020). The total amount of precipitation in the top 1% of heaviest days has increased by around 60% in the Northeast and 45% in the Midwest since 1958 (Figure 2.7). Both of these regions have also experienced increases in river and stream flooding (Mallakpour and Villarini 2015; Davenport et al. 2021). There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US (Diffenbaugh et al. 2018; Kirchmeier-Young and Zhang 2020). Paleoclimate records derived from tree ring growth provide evidence that summer moisture has increased over the past century in parts of New England

(Pederson et al. 2013), the central eastern US (McEwan et al. 2011), and the northern Mississippi River valley (Pederson et al. 2015).

Figure 2.7. Increases in the Frequency and Severity of Heavy Precipitation Events



CAPTION: Observed change in extreme precipitation characteristics: (left) total precipitation falling on the heaviest 1% of days, (center) daily maximum precipitation in a 5-year period, and (right) the annual heaviest daily precipitation amount over 1958-2021. Source: NOAA NCEI and CISESS NC.

Drought Risk Is Complex and Changing

Droughts have become less frequent in the eastern regions of the country since the late 19th century, largely because of increases in precipitation (Figure 2.4; App. 4; McCabe et al. 2017). However, there is evidence that the likelihood of drought in the Northeast did not decrease as much as would be expected given these wetter conditions (Krakauer et al 2019). By contrast, the Southwest is currently experiencing the driest 22-year period in at least the past 1,200 years (Williams et al. 2022), driven largely by warming temperatures that dry the soil (Williams et al. 2020). Droughts in the region are lasting longer (Andreadis and Lettenmaier 2006) and reflect not a temporary extreme event but a long-term aridification trend—a drier “new normal” (Overpeck and Udall 2020).

While droughts are generally thought of as extended events lasting months, years or even decades, “flash droughts” can materialize in a matter of days, driven by extreme high temperatures or wind speeds and a lack of rainfall (Otkin et al. 2018). These events are relatively short-lived but are difficult to predict and prepare for and can have outsized impacts (Pendergrass et al. 2020). An unprecedented flash drought in 2017, the worst on record in many parts of the northern Great Plains, caused severe economic and ecological damage (Gerken et al. 2018). In 2016 the Northeast experienced low winter snowfall followed by a warm, dry summer,

causing a flash drought that challenged water resource managers throughout the region (Sweet et al. 2017). There is evidence that while the frequency of such flash droughts is not increasing, they are drying out soil more quickly as the world warms (Qing et al. 2022).

Storms Are Changing

Changes in specific types of storms are also apparent. Over the past three decades, heavy snowfalls have been more frequent over the Northeast (Cohen et al. 2018), a trend consistent with warming in the western Atlantic Ocean and Arctic air outbreaks from polar vortex disruptions (Cohen et al. 2021). Atmospheric rivers along the Pacific coast have become warmer over the past several decades (Gonzales et al. 2019) and have transported larger amounts of moisture into the West because of increases in Pacific Ocean temperatures (Gershunov et al. 2017).

There is no long-term trend in the frequency of landfalling hurricanes in the United States since the late 19th century, but there has been an increase in basin-wide hurricanes and major hurricane activity in the North Atlantic since the early 1970s (Knutson et al. 2019; Vecchi et al. 2021). In addition to recent increases in storm frequency, evidence continues to build that hurricanes are changing in other dangerous ways. Tropical cyclones have been intensifying more rapidly since the early 1980s (Kishtawal et al. 2012; Bhatia et al. 2019), leaving communities with less time to prepare. Hurricanes tend to lose energy as they move away from the ocean, but the rate of this hurricane “decay” has slowed since the 1960s, allowing storms to extend somewhat farther inland (Li and Chakraborty 2020). There has been a 17% decrease in the speed of movement of storms in the North Atlantic basin since 1900 (Kossin 2019), as well an increased tendency for storms along the North American coast to meander and stall since the 1950s (Hall and Kossin 2019). Slower-moving storms can result in more heavy rainfall, wind damage, storm surge, and coastal flooding; notably, after accounting for changes in the value of property and other assets placed in harm’s way, hurricane damage in the United States has generally increased since 1900 (Grinsted et al. 2019). In addition, emerging evidence suggests a trend that tropical cyclone activity in the North Atlantic has begun earlier in the year since 1979 (Truchelut et al. 2022).

Changes in smaller-scale, short-lived severe weather such as tornadoes and thunderstorms are more difficult to assess, and direct observations of those events and the conditions associated with them are incomplete (Taszarek et al. 2021). While the average annual number of tornadoes appears to have remained relatively constant, there is evidence that tornado outbreaks have become more frequent (Tippett et al. 2016), that tornado power has increased (Elsner et al. 2019), that tornado activity is increasing in the fall (Moore 2018), and that Tornado Alley has shifted eastward (Gensini and Brooks 2018). The complexes of thunderstorms that bring substantial precipitation to the central United States during the warm season have become more frequent and longer-lasting over the past two decades (Hu et al. 2020).

Fire Risk Is Increasing Due to a Combination of Weather and Policy

Much of the country is experiencing more intense and frequent wildfires associated with extreme heating and drought (Higuera and Abatzoglou 2021; Iglesias et al. 2021) and aggravated by the reduction in Indigenous land-use and fire stewardship practices that have been critical for past management of fires (Carter et al. 2021; Higuera et al. 2021). Over the past 1,000 years, warm temperatures and droughts have tended to increase the area burned by wildfires in the West, including the Pacific Northwest and Rockies (Hessburg et al. 2019). In the Rockies, higher temperatures, changes in precipitation, and fire stress have led to major ecological changes, including the disappearance of forests (Ch. 7; Calder and Shuman 2017). Fire history records derived from tree rings and fire scars from forests in the Rocky Mountains show that for most of the past 2,000 years, cooler, wetter conditions, combined with Indigenous fire stewardship practices, limited fires (Higuera et al. 2021). However, greenhouse gas-induced warming and drying, combined with policies that have limited Indigenous sovereignty, have led to new extreme fire regimes and more frequent fires.

Both lightning-caused and human-caused fires were more frequent between 1992 and 2012 (Balch et al. 2017). While rising populations, development, and a growing wildland–urban interface contribute to the increase in human-caused fires (Radeloff et al. 2018), there is no clear evidence of changes in lightning activity (Cummins and Murphy 2009; Villarini and Smith 2013; Kalashnikov et al. 2022b). The increasing trend in lightning-caused fires is therefore largely driven by the increasing aridity in the western United States that results in drier and more flammable vegetation.

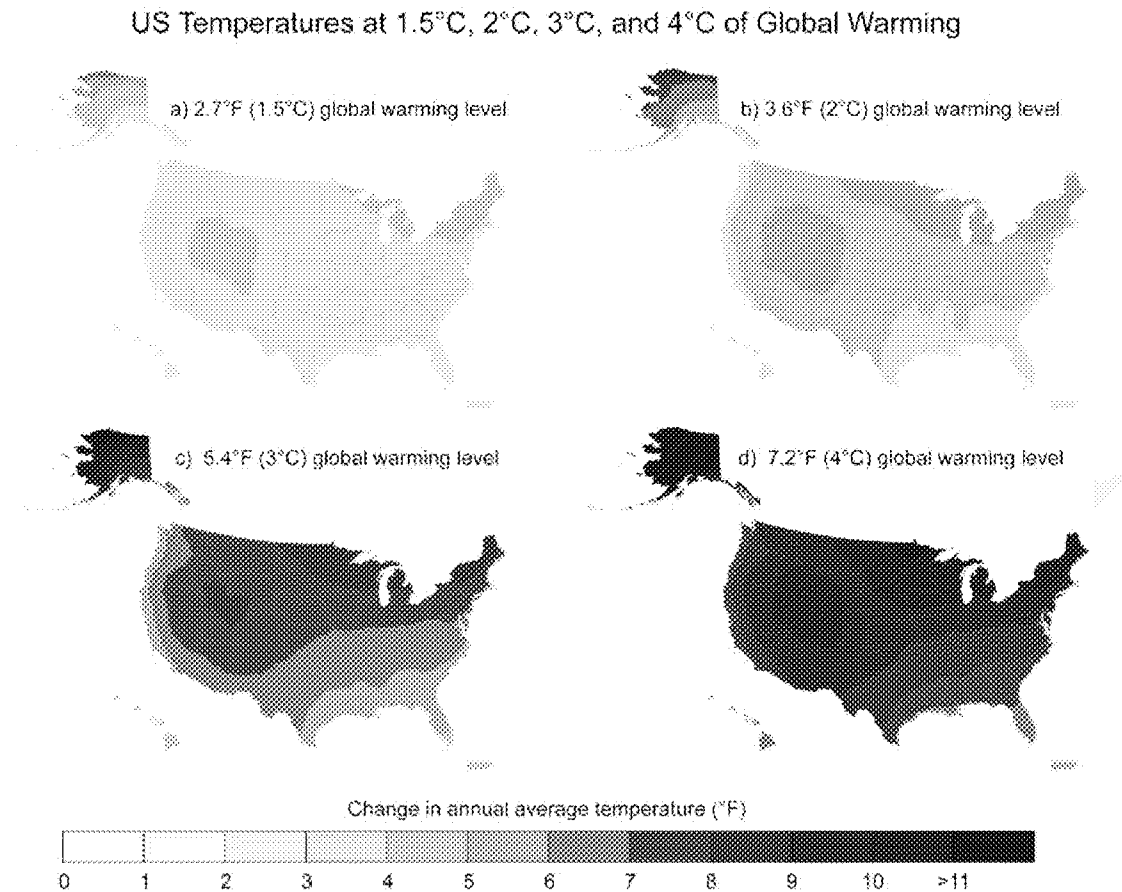
Key Message 2.3. The Future Is in Our Hands

The more the planet warms, the greater the impacts—and the greater the risk of unforeseen consequences (*very high confidence*). Scientists understand much about the Earth system, but there are still uncertainties about how the planet will react to rapid warming. Risks increase with warming, and warming increases with emissions (*very high confidence*). Reducing emissions would limit future warming (*very high confidence*) and the associated increases in risks (*medium confidence*). While worst-case scenarios cannot be ruled out, the future is largely in our hands.

As the World Warms, the United States Warms More

Every increment of global warming leads to larger regional changes in temperature (Figure 2.8). At a global warming level (GWL) of 2°C above preindustrial temperatures, the average temperature across the United States is *very likely* to increase between 4.4° and 5.6°F (2.4° and 3.1°C). For every additional 1°C of global warming, the average US temperature is projected to increase by around 2.5°F.

1 **Figure 2.8. US Average Temperatures at 1.5°, 2°, 3°, and 4°C of Global Warming**

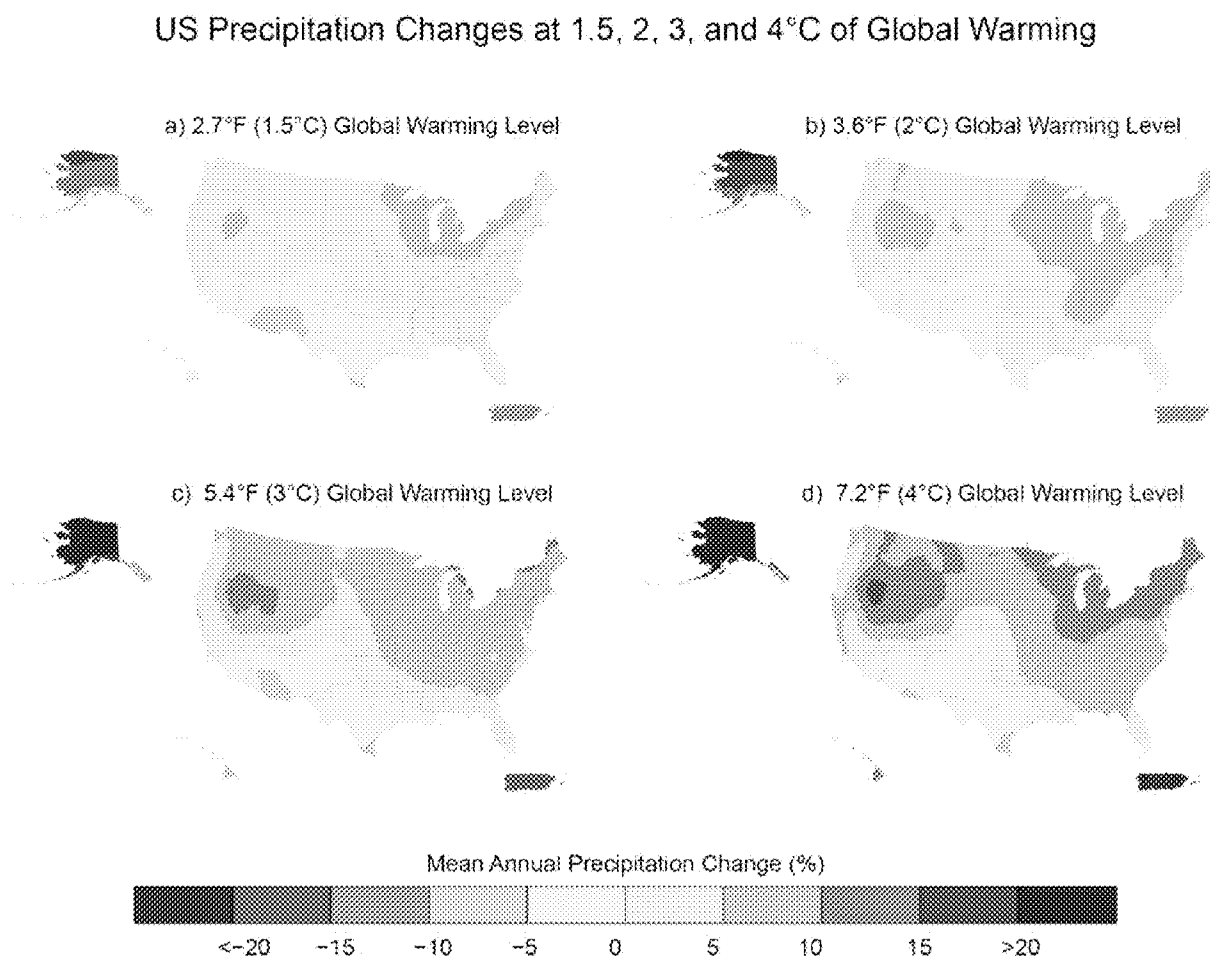


2
3 CAPTION: These maps show changes in mean annual temperature (°F) for various global warming levels
4 (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1991–2020. Based on CMIP6. Source:
5 NOAA NCEI and CISS NC.

6 **Some Regions Will Get Wetter, While Others Will Get Drier**

7 Precipitation changes also scale with global warming, but these projections vary by location
8 (Figure 2.9) and are less certain than temperature changes. As global temperatures increase,
9 annual mean precipitation is projected to increase in the northern and eastern regions of CONUS
10 and in Alaska and to decrease in the Southwest, Texas, and the Caribbean. Changes to the
11 seasonal cycle of precipitation are also expected: in the Northwest and Southeast, precipitation
12 increases will disproportionately occur during the winter wet season (Marvel et al. 2021), while
13 in the Northern Great Plains and Midwest, where the bulk of rainfall is delivered by storms in the
14 warm season, peak rainfall will arrive earlier in the year (Marvel et al. 2021). In a warmer world,
15 less precipitation will fall as snow, leading to large reductions in mountain snowpack and
16 decreases in spring runoff in the mountain West (Chs. 27 and 28).

1 **Figure 2.9. US Precipitation Changes at 1.5°, 2°, 3°, and 4°C of Global Warming**



2
3 CAPTION: These maps show changes in mean annual precipitation (%) for various global warming levels
4 (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1991–2020. Based on CMIP6. Source:
5 NOAA NCEI and CISESS NC.

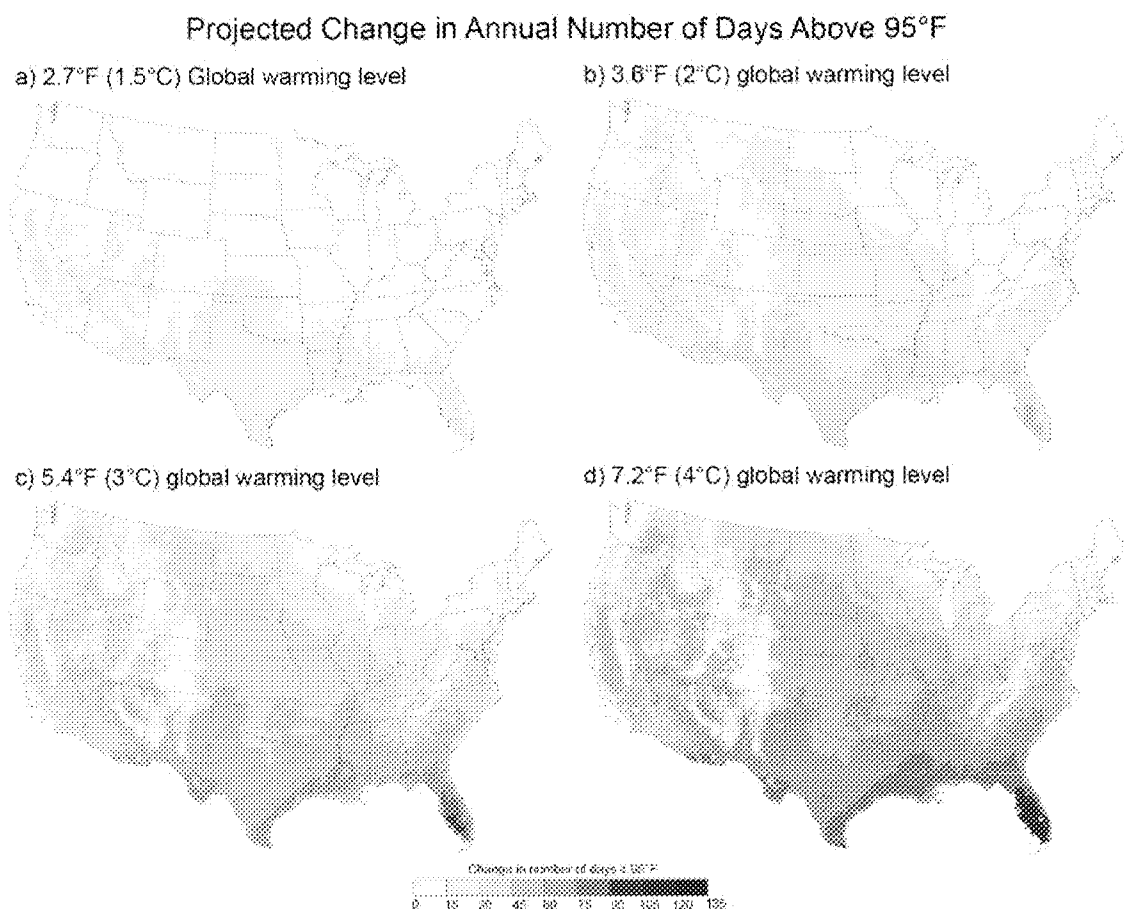
6 **The Risk of Extreme Weather Increases with the Global Warming Level**

7 Recent trends in extreme heat and precipitation foreshadow what is to come in a warmer world.
8 The connection between warming and heatwaves is well understood and documented (Ch. 3),
9 and there is *very high confidence* that heatwaves will increase in severity and duration as
10 warming continues. Figure 2.10 shows projected changes in the number of days over 95°F for
11 three different global warming levels. As the planet warms, heat extremes increase: at a global
12 warming level of 4°C, for example, several southern states will experience more than 80
13 additional days with temperatures over 95°F. As the world heats up, multiday heatwaves are
14 expected to last longer, affect a larger spatial extent and become more severe, exposing more
15 people and infrastructure simultaneously and for longer periods (Lyon et al. 2019). Increases in
16 extreme heat combined with rising humidity are also projected to increase the risk of single and

multiday humid-heat heatwaves across the densely populated Northeast, Southeast, and parts of the Southwest (Mukherjee et al. 2021).

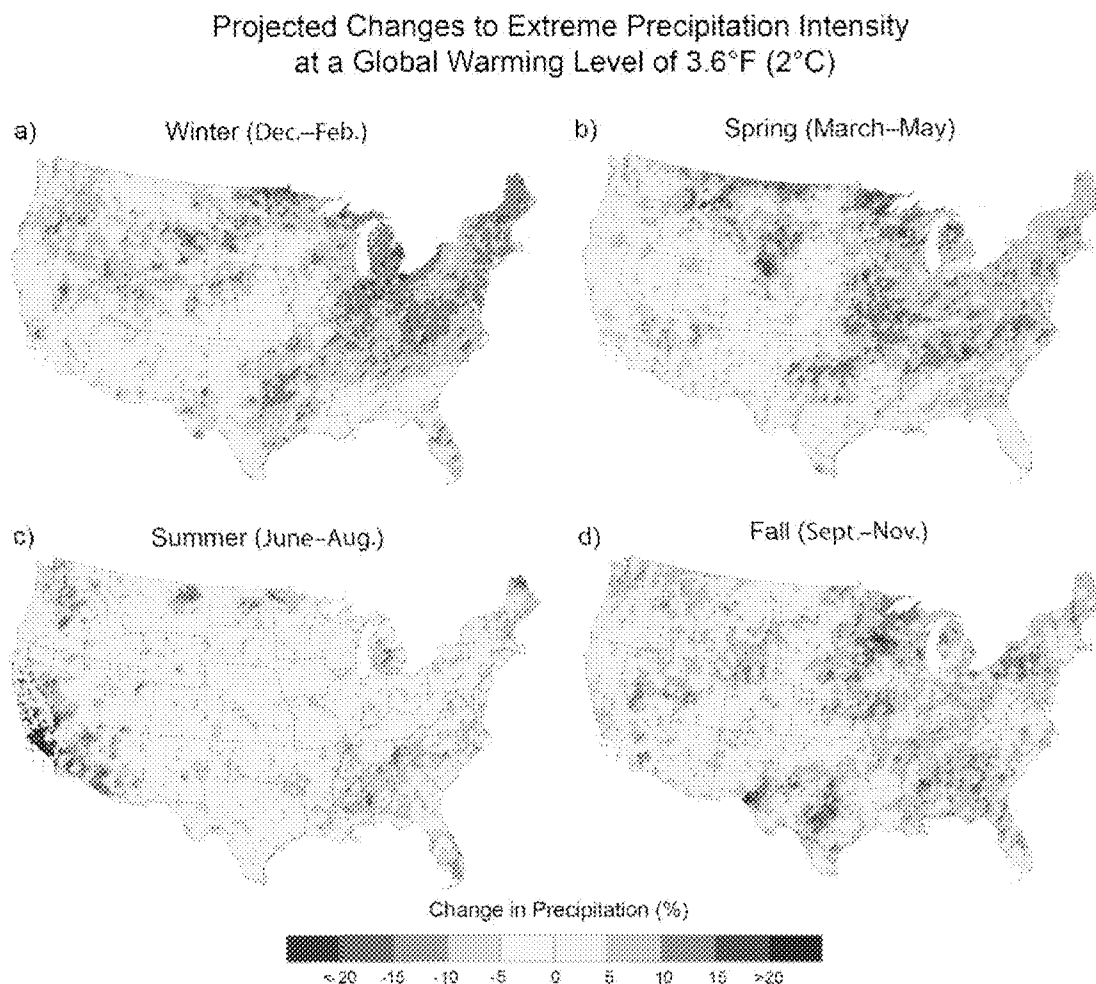
Similarly, scientists are confident that weather systems ranging from tropical cyclones to atmospheric rivers (Knutson et al. 2020; Baek and Lora et al. 2021) will produce heavier precipitation at higher global warming levels (Kirchmeier-Young et al. 2020). Figure 2.11 shows that in most seasons and across most of the US, the intensity of extreme precipitation events is projected to increase with higher global warming levels. The frequency of these extreme precipitation events is also projected to increase across most of the US, even with 1.5° to 2°C global warming (Diffenbaugh et al. 2018; Swain et al. 2020). As with observed trends, changes in extreme precipitation events differ seasonally—changes are more robust and widespread in spring and winter seasons across much of the US and in the eastern and western states in the fall but very limited in the summer season (Akinsanola et al. 2020).

Figure 2.10. Projected Change in Number of Days Above 95°F



CAPTION: These maps show changes in the projected number of days with a maximum temperature over 95°F for various global warming levels (1.5°, 2.0°, 3.0°, and 4.0°C). Changes are relative to the period 1991–2020. Based on LOCA2. Data for projected changes were not available for Alaska, Hawai'i, or the US. Caribbean. Source: NOAA NCEI and CISESS NC.

1 **Figure 2.11. Projected Changes to Precipitation Extremes**



2

3 CAPTION: These maps show projected changes in the amount of precipitation falling in the heaviest 1%

4 of events (99th percentile of the distribution) for a GWL of 2°C. Changes are relative to the period 1991–

5 2020. Based on LOCA2. Data for projections were not available for Alaska, Hawai'i, or the US Caribbean.

6 Source: NOAA NCEI and CISESS NC.

7 Even as downpours increase, the risk of drought also rises with the global temperature. In the

8 Southwest, multidecadal droughts analogous to or drier than the 2000–2021 drought are

9 projected to increase in the future—regardless of global warming level (Cook et al. 2021; Ch.

10 28). This is due to projected decreases in springtime precipitation that, combined with warmer

11 temperatures, push the region into a new and drier average state (Overpeck and Udall 2020).

12 However, the risk of single-year droughts analogous to the driest recent year (2002) increases by

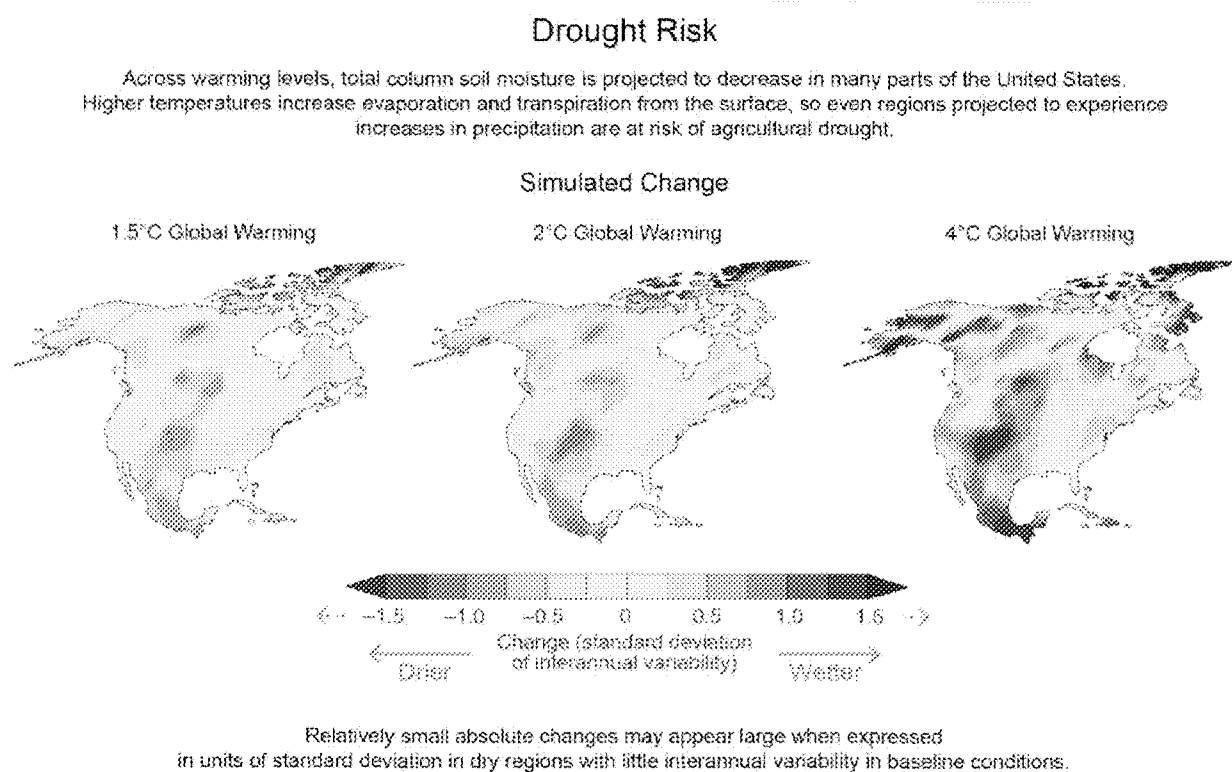
13 8% at a GWL of 2°C but by 24% at 4°C (Cook et al. 2021). Limiting global warming would also

14 reduce the severity of inevitable multidecadal droughts by reducing the magnitude of extreme

15 single-year droughts during these events.

Other regions are not projected to aridify to the same extent as the Southwest, but the risk of short-term drought increases nevertheless as the temperature rises. Because evaporation increases with warming, surface soil moisture is projected to decrease over much of the Nation (Figure 2.12). This means that future agricultural droughts are likely to be more severe and last longer as the planet warms (Cook et al. 2020). The past may provide insight into what could happen as temperatures continue to warm. Paleoclimate datasets show that the already-water-stressed Great Basin region, which includes Nevada, parts of Utah and Wyoming, and much of the Southwest, experienced severe drought throughout the mid-Holocene (approximately 5,000–9,000 years ago), when the Western Pacific was warm, Arctic temperatures were high, and there was less sea ice—all global changes projected in a future warmer world (Lachniet et al. 2020).

Figure 2.12. Projected Soil Moisture Changes at Different Global Warming Levels



CAPTION: Annual mean total column soil moisture change (standard deviation). Projected soil moisture drying intensifies and becomes more widespread as the global warming level increases. Adapted from Figure SPM.5 in IPCC 2021b.

While less well understood than heat waves or downpours, there is increasing evidence that the characteristics of several storm types and their impacts will change in the future. With every increment of global warming, projected sea level rise will lead to higher storm inundation levels when storms do occur (Ch. 9), projected increases in water vapor will lead to more extreme rainfall rates, and projected increases in water temperatures will result in stronger storms (with winds 5% faster at a GWL of 2°C) and an increase in the proportion of Category 4–5 hurricanes.

Studies suggest, albeit with mixed or lower certainty, that the overall frequency of tropical storms will decrease, while the frequency of Category 4–5 storms will increase (Knutson et al. 2020). Even in regions that experience an overall decrease in precipitation, atmospheric rivers are projected to become stronger and wider (Espinoza et al. 2018; Payne et al. 2020), increasing the risk of downpours and floods across the western United States (Gershunov et al. 2019; Rhoades et al. 2021; Payne et al. 2020; Baek and Lora 2021). In addition, the paleoclimate record shows that the locations along the West Coast where storms bring moisture may also shift with warming (Lora et al. 2017).

Modeling studies generally project increases in the frequency of weather environments that give rise to severe thunderstorms in the United States during spring and fall under stronger warming scenarios (Allen 2018; Trapp et al. 2019). These changes may also lengthen the severe storm season as the world warms, especially in the Midwest and Southeast during cool-season months (Haberlie et al. 2022).

Compound Event Risk

Warming increases the risk of individual extreme weather events. It also increases the risk of experiencing multiple extreme events simultaneously, in quick succession, or across several different regions (see Focus on Compound Events).

Co-occurring hot and dry conditions are projected to become more frequent as the world warms (Alizadeh et al. 2020; Li and Chakraborty 2020; Ridder et al. 2022), suggesting increases in the risk of simultaneous heatwaves and droughts, elevated wildfire risk, and severe impacts on water resources and freshwater and marine ecosystems. Extreme wildfire events followed by extreme precipitation within the following year are projected to increase across the West (Touma et al. 2022), which could increase the risk of post-fire debris flows, landslides, and flash floods. The largest increases are expected in the Pacific Northwest, where this risk has historically been low. As global temperatures increase, the Atlantic and Gulf Coasts are projected to experience increases in compound flooding from rising sea levels, higher storm surge from stronger storms, and increased flooding from heavier precipitation, impacting people, ecosystems, and infrastructure along our coastlines (Wahl et al. 2015; Ch. 9).

Global Warming Causes Long-Term Sea Level Rise

The most substantial differences in projected sea level rise for the United States for different global warming levels begin to arise at the end of this century, due to uncertainty in the trajectory of rapid ice loss from the Antarctic ice sheet (Robel et al. 2019; Edwards et al. 2021). A GWL of 2°C would lead to a likely sea level rise in CONUS of 2–3 feet in 2100 and 2.5–5 feet in 2150, relative to 2000 sea levels. Every additional degree Celsius of global warming is likely to cause at least 4 inches of additional sea level rise in CONUS in 2100 and at least 7 inches of additional sea level rise in 2150 (Sweet et al. 2022). At a 2°C GWL, it is very unlikely, but not impossible, that sea level rise in CONUS would exceed 4 feet in 2100 and 7 feet in 2150. At higher GWLs,

such extreme sea level rise becomes more likely within the next 100–150 years. The total rise in sea level that will be realized beyond 2150 can differ by many feet depending on global warming levels over the next 50–100 years due to the potential for rapid and irreversible loss of ice from Greenland and Antarctica starting next century (Aschwanden et al. 2019; DeConto et al. 2021; Lowry et al. 2021). Such significant changes at 2100 and beyond translate directly into substantially increased frequency of flooding events in coastal regions, making major flooding events in some regions as common in 2100 as minor flooding events are currently (Sweet et al. 2022).

Global Warming Changes the Oceans

Sea surface temperatures increase with the global warming level, but changes are not uniform across the globe; northern oceans are expected to warm faster than the tropics. Heat will continue to accumulate in the shallow and deep oceans: at a GWL of 4°C, the West Coast and Alaska could accumulate 3 to billion Joules per square meter, the East Coast 5 billion Joules per square meter, and the Gulf of Mexico up to 6 billion Joules per square meter—roughly the energy equivalent of two hundred pounds of TNT per square foot. As a result, the risk of marine heatwaves is projected to increase as the world warms. Projections indicate an increase of between 150 and 300 marine heatwave days per year at a GWL of 2.5°C. It is therefore possible that the coastal oceans of the United States could enter into near-permanent heatwave status, with significant ramifications for marine life (Jones et al. 2018). The probability that September sea ice completely disappears from the Arctic Ocean, including Alaska coastal water, rises from 1% in 2100 under a GWL of 1.5°C to 10%–30% at a GWL of 2°C (IPCC 2019).

Projections of changes in ocean acidification and oxygen loss in US waters vary with location. At elevated global warming levels, the chemistry of waters in the Gulf of Maine will change in ways damaging to shell-building organisms, with the saturation level of aragonite—a form of calcium carbonate used by shell-building marine life—projected to fall below a crucial shell-building threshold for most of the year (Siedlecki et al. 2021). Ocean oxygen loss in the upper and middle depths will be most pronounced for the United States in the North Pacific, including off the coasts of Alaska and the West Coast, which will cause a habitat squeeze for marine life moving away from warming waters at the surface (Gong et al. 2021; Kwiatkowski et al. 2020).

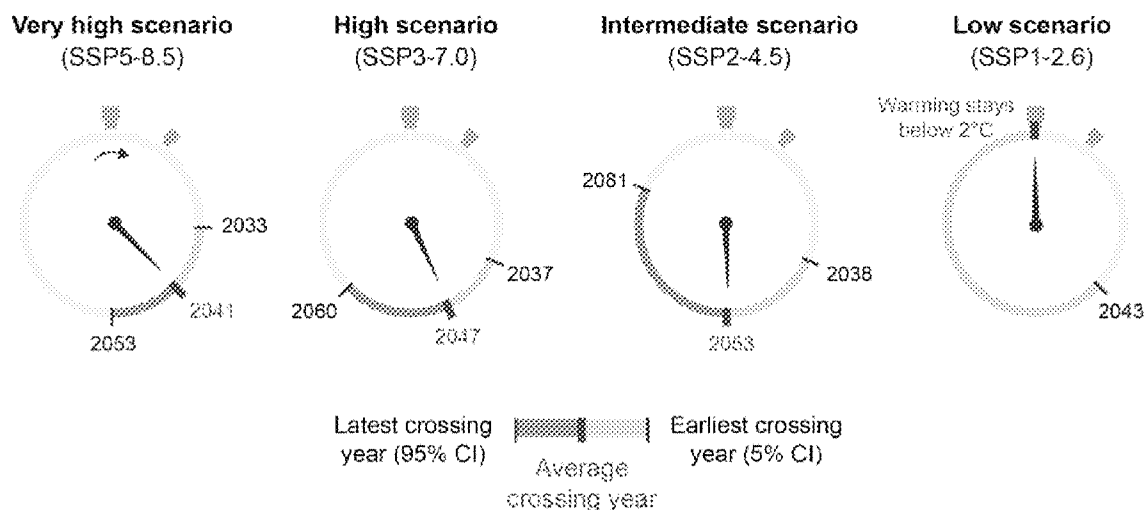
When or if We Reach a Particular Threshold Depends on Future Emissions

Projections of future global mean surface temperature primarily depend on two things: 1) future emissions and 2) how sensitive the climate system is to these emissions. In a very high emissions scenario, the world is *very likely* to exceed a global warming level of 2°C between 2033 and 2053, depending on the climate sensitivity to greenhouse gas emissions (Ch. 3). In a low emissions scenario, by contrast, the world is *very likely* not to cross this threshold at all (Figure 2.13). In addition to warming *more*, in high and very high scenarios, the Earth warms *faster*. The occurrence of some record-shattering extremes is dependent on this rate of warming (Fischer et

al. 2021). Faster climate change also increases the challenge of adaptation for both human and natural systems.

Figure 2.13. Global Surface Temperature Change

Future emissions of greenhouse gases determine whether and how quickly we reach 2°C of global warming.



CAPTION: IPCC AR6 assessed warming projections across different shared socioeconomic pathways (SSPs), with specific global warming levels highlighted. Source: NOAA NCEI and CISESS NC.

Over the past few years, a number of groups have suggested that we can narrow the plausible range of current emissions outcomes based on policies in place today, putting the world on track for a central estimate of around 2.6°C (ranging from 2°–3.7°C) by 2100 (UNEP 2021; IEA 2021; Sognaes et al. 2021; Hausfather and Peters 2020; Hausfather and Moore 2022; Meinshausen et al. 2022). However, current policy projections represent neither a ceiling nor a floor on future climate outcomes. Our choices matter; global surface temperatures will continue to rise until greenhouse gas emissions reach net-zero, and surface temperatures are not expected to fall for centuries in the absence of net-negative emissions. At the same time, Earth system models suggest that only a small amount of additional surface warming is expected once we reach net-zero, at least under scenarios where global warming is limited to 2°C or below by 2100 (MacDougall et al. 2020). In other words, additional warming is not “locked in” after net greenhouse gas emissions fall to zero.

Some Impacts Are Inevitable Because of Past Choices

While the Earth is likely to stop warming if emissions reach net zero, the climate system is not done responding to past emissions. Because the CO₂ not removed by sinks on land and in the

ocean remains in the atmosphere for thousands of years, the accumulation of past emissions already makes some impacts inevitable. Certain slow-moving aspects of the climate system, such as ice sheets and the deep ocean, take decades or centuries to respond to changes. This means that even in a low scenario where global warming slows or stops, some climate changes will continue.

Some Ocean Changes Are Locked in Even Under Aggressive Mitigation Scenarios

Past emissions will continue to affect the ocean for thousands of years. Regardless of future emissions, the surface ocean will continue to take up heat from the atmosphere, accumulating 2–4 times as much heat as has been taken up since 1970, even under low or very low scenarios (IPCC 2019). This heat will have cascading effects on marine ecosystems, increasing the probability of marine heatwaves and causing sea level rise due to the expansion of warm water. Even after the world reaches net-zero emissions, oceans will continue to acidify, as they gradually absorb the atmospheric CO₂ produced by past human activities.

Sea Level Rise Will Continue to Accelerate

On timescales relevant to infrastructure planning (around 30 years), sea level along US coastlines is expected to continue rising at accelerating rates above the global average. Under a range of potential global warming levels, average sea level along the US coast is likely to be between 12 and 20 inches above 2000 sea levels in 2050 (Sweet et al. 2022). At these short timescales, regional variations in projected sea level rise are large, with 4–12 inches of sea level rise likely in the Pacific Northwest and 20–27 inches of sea level rise likely in the western Gulf of Mexico. Future projected changes in sea level will likely lead to an increased frequency of coastal flooding events in the continental United States over the next 30 years, with a greater than tenfold increase in typically damaging flooding events (e.g., storm surge currently recurring every few years) and a fivefold increase in destructive flooding events (e.g., major storm surge events currently recurring once in many decades) over this time period (Sweet et al. 2022).

The Nation Has No Choice But to Adapt to a Changing Climate

It is not possible to prevent climate change: the current global warming level is already 1.2°C. The Nation must both adapt to this new reality and prepare for at least some level of additional warming. Inertia in the world's infrastructure (Fisch-Romito et al. 2021) and economic and political systems (Roberts et al. 2018) means that the near-term trend in risk over the next few decades is largely independent of the choice of emissions scenario (UNEP 2021), and the climate benefits of aggressive action to reduce greenhouse gas emissions are unlikely to be realized in the near term. This means the Nation will need to adapt to a changing climate regardless of future emissions.

We Cannot Rule Out Catastrophic Outcomes

Climate Sensitivities Exceeding 4°C Are Unlikely But Not Impossible

There is no known precedent for a species changing its own climate as quickly as we are changing ours, and there are many uncertainties associated with a rapidly warming world. Low-probability and potentially catastrophic outcomes are not impossible, and these risks persist even under current policies. While recent assessments (Sherwood et al. 2020) put the *likely* range of equilibrium climate sensitivity—the long-term warming the world will experience if atmospheric CO₂ concentrations are doubled—between 2.6° and 3.9°C, higher values are not definitively ruled out, and feedback loops such as changes to cloud cover may lead to more warming in the future. Similarly, we cannot rule out a GWL of 4°C or more this century, particularly if climate change strongly reduces the ability of the biosphere or ocean to remove carbon from the atmosphere (Ch. 3).

Changes to the Carbon Cycle May Increase the Amount of CO₂ in the Atmosphere

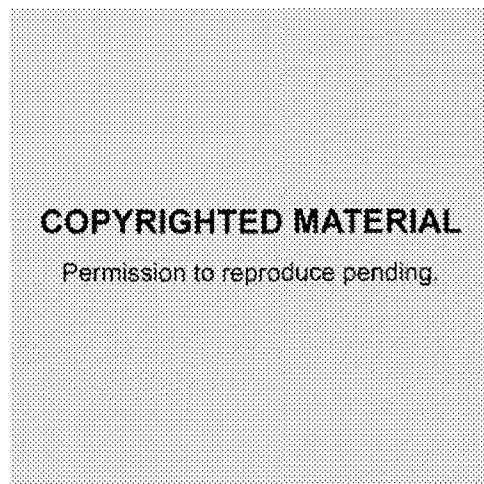
Our emerging understanding of land, ocean, coastal, and freshwater systems suggests the possibility of a decline in future carbon uptake capacity (Huntzinger et al. 2018). For example, the processes of photosynthesis, respiration, and decomposition strongly depend on temperature and moisture availability, and changes in either can alter the balance of carbon uptake and release across terrestrial ecosystems (Ch. 7). Similarly, because of the temperature sensitivity of gas solubility in water, higher temperatures caused by climate change also affect the rate and extent to which atmospheric CO₂ is exchanged with ocean and freshwater systems. Although ocean carbon uptake and storage has increased in response to increased carbon emissions from 1960 to 2020, climate models project that the fraction of emissions taken up by oceans will decline as CO₂ concentrations increase (Lovenduski et al. 2019; Canadell et al. 2021) but there are significant differences in regional responses and their underlying mechanisms.

Furthermore, some land reservoirs, such as tropical forests or the Arctic–boreal ecosystems, could switch from a net sink to a net source of carbon to the atmosphere (e.g., Schimel et al. 2015). For example, carbon emissions from the Arctic have the potential to increase significantly as temperatures rise and the vast stores of soil carbon gradually thaw. There is estimated to be about 4.8–5.9 trillion tons of carbon (Hugelius et al. 2014) frozen down to 20 meters in Arctic permafrost. This is roughly double the amount currently in the atmosphere and more than three times what already has been emitted to the atmosphere from fossil fuel use since preindustrial times. As the Arctic warms and permafrost thaws, this ancient carbon may be mobilized to the atmosphere, primarily as CO₂, with a small fraction (about 3%) emitted as methane. Multiple studies (Schuur et al. 2018; Meredith et al. 2019) point out that potential carbon emissions from the Arctic could have important implications for policies aimed at reducing or stabilizing emissions— simply because a warming Arctic has both regional and global climate implications.

Tipping Elements Could Lead to Regional Rapid Changes

Tipping elements are components of the Earth system that may respond nonlinearly to human-caused climate change by transitioning toward substantially different long-term states upon passing key thresholds, or “tipping points.” In some cases, such changes could produce additional greenhouse gas emissions that could compound global warming (Lenton et al. 2008; Kopp et al. 2016).

Figure 2.14. Proposed Regional Tipping Elements



Caption: Spatial distribution of proposed regional climate tipping elements. Source: Wang et al. 2023.

Systems that have been identified as possible tipping elements include slowdown of the Atlantic Meridional Overturning Circulation, Arctic permafrost thaw, loss of the Greenland and West Antarctic ice sheets, Arctic sea ice loss, boreal forest shifts, disruption of tropical seasonal monsoons, Amazon rainforest dieback, tropical coral reef loss, and the disappearance of cloud decks that currently reflect sunlight, cooling the Earth (Figure 2.14, Wang and Li 2022). While some of these tipping elements are represented in modern Earth system models, many are still not, and the precise response of these systems to rapid climate change remains poorly understood. It is not possible to say that exceeding a particular GWL will trigger these tipping elements, nor are scientists certain that staying below a particular GWL will prevent them. However, the risk of these nonlinear changes increases with every increment of global warming.

Extreme Sea Level Rise Cannot Be Ruled Out

Increases in sea level in the continental United States of 3–6 feet by 2100 and 3–12 feet by 2150, depending on human emissions, are distinct possibilities that cannot be ruled out (i.e., have at least 1% chance of occurrence with global warming levels of 1.5°–4°C; Edwards et al. 2021; DeConto et al. 2021; Sweet et al. 2022). Sea level rise imposes risks to coastal communities and cities through increasing frequency of high tide flooding and storm surge. These tail risks,

potential low-likelihood but high impact outcomes, are expensive: planning for catastrophic outcomes makes adaptation much more costly (Buchanan et al. 2016; Hasnoot et al. 2020).

The Biggest Uncertainty Is What We Will Do

Despite uncertainties in how land, ocean, atmosphere, and ice will respond to warming, and despite internal variability in the climate system, the largest source of uncertainty is the trajectory of our greenhouse gas emissions. This is within human control and depends on our collective policy, economic, and social choices. Although we probably will not be able to detect climate benefits from even the most aggressive possible emission reductions before the middle of the century given the magnitude of internal climate variability, there are numerous co-benefits to mitigation in the near term, including improvements to air quality and health, reductions in mortality, and benefits to agriculture, the economy, and the labor market (Shindell et al. 2020).

Rapid reductions in emissions can still limit global temperature changes to well below 2°C (Meinshausen et al. 2022). Global temperatures can be limited to 1.5°C above preindustrial levels by 2100 in scenarios where global emissions reach net zero in the middle of this century with modest deployments of net-negative emissions thereafter (Rogelj et al. 2018), although most scenarios have at least some midcentury temperature overshoot, which could result in irreversible consequences to global ecosystems (Ch. 8; O'Neill et al. 2022). Still, the degree to which climate change will continue to worsen is in large part up to humans. The faster and the further we cut emissions, the less future warming will occur, and the safer we will be from climate change.

Traceable Accounts

Process Description

Most team members were selected from the pool of nominations received via the public call for authors; others were identified through extended networks to ensure diverse representation across multiple axes. The following areas of expertise were identified as crucial for Chapter 2:

- Paleoclimate and long-term context for climate trends
- Carbon cycle observations and greenhouse gases
- Infrastructure and resilience scenarios and projections in the CMIP6 (Coupled Model Intercomparison Project, Phase 6) models
- Regional trends
- Hurricanes, tropical cyclones, and midlatitude storms
- Ocean trends
- Cryosphere and sea level rise
- Climate extremes
- Diverse leadership in science
- Observations of climate trends

Author meetings were held virtually biweekly. Consensus was built by referring to the literature and leveraging the specific expertise of chapter authors. Engagement with other chapters occurred through formal presentations at the April 2022 chapter leadership meeting and one-on-one meetings between chapter lead authors.

Key Message 2.1. Climate Is Changing, and Scientists Understand Why

Description of Evidence Base

The evidence base for anthropogenic increases in greenhouse gases (GHGs) is extensive and includes satellite and ground-based observations, solid theoretical understanding, and coherent measurements across multiple systems. Evidence for changes in aerosols includes long-term satellite and ground-based observations. Evidence for warming and other long-term climate changes has been extensively documented across multiple variables. Observations at smaller scales are noisier and regional signals more difficult to separate from natural internal climate variability.

Observational surface temperature records are available from a wide variety of scientific groups (e.g., Hansen et al. 2010; Vose et al. 2021; Morice et al. 2021; Rohde and Hausfather 2020). These temperature records combine land surface temperature data from weather stations with

ocean sea-surface temperature records from sources including ships and buoys. These records are corrected for inhomogeneities introduced by changes in measurement techniques over time and use various different interpolation techniques to estimate temperature anomalies between measurement locations.

Seasonal average and extreme precipitation changes are widely documented using observations, and changes are consistent with our physical understanding. The evidence base for ocean changes includes long term surface and subsurface ocean observations of temperature, salinity, oxygen, and pH in the coastal and open ocean and satellite data.

Paleoclimate evidence includes multiple proxy-based reconstructions and modeling.

Sea level rise over the industrial era has been measured with local tide gauges and satellite altimetry (since the 1970s). Changes in the processes contributing to sea level rise (ocean thermal expansion, glacier and ice sheet melt, and terrestrial freshwater discharges) have been independently measured using in situ techniques in the ocean (e.g., floats, ship-based measurements) and on ice sheets, as well as remotely (e.g., satellite gravimetry and interferometry). Changes in sea ice and lake ice over the past several decades at the poles have been extensively documented from satellites, including visible imagery, altimetry, and microwave backscatter.

Drought has many definitions including meteorological drought, snow drought, and soil moisture drought and can be defined on timescales ranging from flash droughts to multidecadal megadroughts. The level of uncertainty in drought changes in several regions depends on the definitions and metrics used and the sources of measurements. Surface-based measurements of soil moisture are limited and reliable satellite-based measurements of soil moisture are less than a decade long.

Major Uncertainties and Research Gaps

Uncertainty in Global Surface Temperature Reconstructions

In recent years, different groups producing global surface temperature records have somewhat converged in methodological approach, drawing on a larger set of collected weather station data (Rohde et al. 2013; Menne et al. 2018) and using more granular interpolation approaches rather than simple latitude/longitude grid-cell averaging (Vose et al. 2021). Published global surface temperature uncertainties on an annual basis range from $\pm 0.13^{\circ}\text{C}$ to $\pm 0.2^{\circ}\text{C}$ in the 1850s when records are more sparse to $\pm 0.03^{\circ}\text{C}$ to $\pm 0.09^{\circ}\text{C}$ at present across different surface temperature datasets, with differences between datasets driven by the number of measurements included, the spatial interpolation approach, and the method of uncertainty calculation (Rohde and Hausfather 2020).

Uncertainty in GHG Emission Inventories

Inventories of GHG emissions are generally estimated using “bottom-up” approaches, wherein emission estimates are based on activity data and emissions factors while removals are based on inventories of carbon stock changes and dynamical model simulations. This bottom-up approach allows for explicit characterization of GHG emissions and removals into specific sectors or categories that are identified in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC 2006, 2019): energy, industrial processes and product use; agriculture, forestry and other land use (AFOLU); waste; and other. These bottom-up methods can provide precise and accurate country-level emissions estimates when the activity data and emissions factors are well quantified and understood, such as for the fossil fuel combustion category of the energy sector. But these estimates can also have significant uncertainty when the emissions processes are challenging to quantify (such as for AFOLU sector) or if the activity data are inaccurate or missing even for the fossil fuel emissions sector (Gurney et al. 2021). A more recent alternative to obtaining GHG emission estimates from bottom-up approaches are the “top-down” estimates. These estimates refer to those constrained by atmospheric measurements and chemistry-transport models in inversion systems. Over the last decade, a larger suite of atmospheric inversions using both in situ and remote sensing measurement are providing improved understanding of regional GHG sources and sinks. However, uncertainties exist between the estimates provided by the bottom-up and top-down approaches (e.g., Kondo et al. 2019; Xu et al. 2021), and various efforts are underway (e.g., Regional Carbon Cycle Assessment and Processes, Phase 2) to increase the level of agreement between the two estimates, thereby yielding more robust knowledge of GHG emissions.

Uncertainty in Arctic Connections to Midlatitude Weather Extremes

Uncertainties in the influence of the Arctic on midlatitude weather extremes remain due to lack of consistency in model responses and observations, particularly for the winter season. Several advances in the physical understanding of how Arctic processes could influence midlatitude extremes in various seasons have been made since the publication of the Fourth National Climate Assessment (USGCRP 2018), yet the mechanisms continue to be a subject of debate in the scientific community.

Description of Confidence and Likelihood

It is unequivocal that global temperatures are increasing, and scientists are *virtually certain* that the planet has warmed between 1.1° and 1.2°C since the beginning of the industrial revolution, based on multiple observational datasets. There is *very high confidence* that this warming is driven by anthropogenic GHG emissions, which have increased by over 47% since 1850 based on modeling studies and theoretical understanding. There is *high confidence* that changes outside the boundaries of the United States affect the Nation’s climate.

Key Message 2.2. Many Extreme Events Are Becoming Worse

Description of Evidence Base

Extreme events are rare by definition, but multiple datasets indicate they are increasing. We have a solid theoretical understanding of how some events (heatwaves, downpours) should increase in a warming world (Ch. 3). Others (e.g., agricultural drought) depend on multiple interacting physical processes. Event attribution now allows us to assign a quantifiable fraction of attributable risk to climate change.

A wide variety of observational evidence exists for the occurrence of different storm types. Trained weather observers and storm spotters create storm reports across the country for severe hail, winds, and tornadoes. The National Weather Service (NWS) WSR-88D radar network maintains nationwide surveillance observations of precipitation, winds, and storm occurrence. The NWS additionally conducts storm damage surveys for high-impact events. NOAA and Air Force Hurricane Hunters conduct surveillance flights into tropical cyclones expected to impact US interests. NOAA and NASA geostationary satellite observations maintain a record of cloud properties and lightning occurrence. However, the length and representativeness of each data source is variable; storm reporting relates to population density and exposure, and the availability of trained observers impacts record quality, especially for transient phenomena such as hail.

Major Uncertainties and Research Gaps

There is growing evidence that the impacts of climate change are, and will be, distributed unequally across US populations due to differences in both exposure and vulnerability. However, there are gaps in understanding the community-level impacts of projected changes in extreme events. Vulnerability at this level is in part a function of our investments (capital, operations, and management) in the built environment that serve to buffer these impacts (e.g., stormwater conveyance and levees to reduce flooding, water storage to relieve water shortages during drought). There is a lack of systematic assessment of these assets and other facets of vulnerability across the United States.

New literature has emerged documenting changes in certain types of compounding extremes such as heat and drought, but the limited observed record hinders quantifying long-term trends in several other compound extremes. Several frameworks for studying various compound extremes have emerged as well, and the physical understanding of certain compound extreme events such as heat/drought, heat/humidity, coastal wind/precipitation/flooding has been documented, yet the understanding of the physical drivers of many other compound extremes is still emerging. Therefore, there is a gap in methodological advances, advances in understanding of their physical drivers, and studies quantifying projections in compound extreme risks.

The lack of homogenized daily and hourly temperature datasets limits our ability to reliably assess the evolution of extreme heat events over century-scale periods, although the availability

of modern reanalysis products has increased agreement in changes in extreme heat events over the past 50 years.

There is limited research on changes in lightning activity, particularly lightning that causes wildfires.

Description of Confidence and Likelihood

There is *very high confidence* that heat waves are becoming more frequent and severe based on multiple observational datasets. There is also *very high confidence* that climate change is and will continue to make rainfall extremes more intense. Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why we also have *very high confidence* that storms are delivering more rainfall and *very high confidence* that storm surges are becoming higher. There is *very high confidence* that the Southwest is experiencing more severe drought: the current multidecadal soil moisture drought is *likely* the worst in the past 1,200 years (Williams et al. 2022). There is *medium confidence* that the eastern region is experiencing reduced drought risk; studies suggest a transition toward more frequent extremes (Stevenson et al. 2022) and indicate that warming may partially counteract the effects of increased precipitation. Other extremes involve more complex interactions between human and natural systems: the occurrence and impacts of wildfires depend on fire ignition and suppression practices. However, we have *high confidence* that the hot and dry weather conditions that elevate fire risk are becoming more common.

Key Message 2.3. The Future Is in Our Hands

Description of Evidence Base

The Shared Socioeconomic Pathways (SSPs) were made available to the broader research community, replacing the old Representative Concentration Pathways (RCPs) and providing a more detailed assessment of the range of possible emissions pathways, as well as mitigation and adaptation challenges across different sets of socioeconomic assumptions (Riahi et al. 2017). A subset of the SSPs served as the basis for CMIP6 scenarios used in this assessment and the Sixth Assessment Report of the IPCC (IPCC 2021a).

CMIP6 provides a large set of model runs to use in evaluating different future emissions pathways and global warming levels. In addition, recent work assessing multiple lines of evidence from observational data, paleoclimate evidence, and physical process modeling has helped narrow the range of climate sensitivity (Sherwood et al. 2020). The IPCC AR6 produced a new set of assessed warming projections based on these climate sensitivity estimates and CMIP6 models that were weighted based on their performance in reproducing historical temperatures.

The IPCC AR6 Working Group III (O'Neill et al. 2022) report explored a wider range of “overshoot” scenarios, where global temperatures temporarily exceed 1.5°C before being reduced through the large-scale use of negative emissions technologies. Additionally, AR6 Working Group I provided a thorough exploration of the zero emissions commitment associated with the cessation of carbon dioxide (CO₂) and other GHG emissions, building off the work of the Zero Emissions Commitment Model Intercomparison project (MacDougall et al. 2020).

Recent literature summarized in the IPCC AR6 Working Group III (O'Neill et al. 2022) and in Hausfather and Moore (2022) provides a clearer sense of expected global mean surface temperature outcomes under scenarios including only current policy, near-term 2030 commitments, and long-term net-zero commitments.

Major Uncertainties and Research Gaps

Major uncertainties remain surrounding the emissions trajectories implied by current policies and the plausibility of worse-than-current-policy emissions outcomes. While most current policy scenarios in the literature project relatively flat global emissions over the next few decades, there are some (e.g., in the IPCC AR6 Working Group III scenario database) in which emissions continue to increase. Similarly, large uncertainties remain when translating near-term and long-term mitigation commitments to global emissions pathways, particularly for non-CO₂ GHGs and other climate forcings like aerosols.

The translation from emissions scenarios to warming outcomes is complicated by uncertainties in both the sensitivity of the climate to emissions (both the transient climate response and the equilibrium climate sensitivity) and carbon cycle feedbacks that may affect the portion of emissions that accumulate in the atmosphere. Specifically for carbon cycle feedbacks, it will be the balance between the response of land and ocean systems to future climate that will determine the strength and extent of carbon uptake by these systems, whether they may become a net source of CO₂ to the atmosphere, and, consequently, the trajectory of future GHG forcings.

While recent work (Sherwood et al. 2020) has meaningfully narrowed the potential range of climate sensitivity, there are still tail risks of outcomes where equilibrium climate sensitivity exceeds 5°C or is below 2°C per doubling of atmospheric CO₂. There is also disagreement between a subset of high-sensitivity CMIP6 models and other lines of evidence supporting a narrower range of climate sensitivity (Hausfather et al. 2022).

On timescales of less than 50 years, the most significant uncertainties in future sea level are due to regional and local variations in sea level rise and the interannual sea level variability intrinsic to the coastal ocean system. In Alaska and New England, the regional gravitational influence of glaciers and ice sheets may cause lower sea level rise or even sea level fall in the future, although the extent of these gravitational effects is highly dependent on the spatial fingerprint of glacier and ice sheet loss, which is uncertain (Larour et al. 2017). Internal variability and human-caused changes in ocean circulation appear to have a strong effect on year-to-year sea level, particularly

in the US Mid-Atlantic coast (Kopp et al. 2014), but are not consistently simulated between models or included in the range of uncertainty in most sea level projections (Sweet et al. 2022).

On longer timescales (2100 and beyond), there are substantial uncertainties in projected sea level rise due to an incomplete understanding (and intermodel differences) of how the Greenland and Antarctic ice sheets will behave in a warmer climate. There is a consensus that past carbon emissions and even relatively moderate future global warming levels commit us to at least 1–2 m of sea level rise over hundreds to thousands of years from the melting of the Greenland and Antarctic ice sheets (Levermann et al. 2013). However, there are many meters of uncertainty remaining both in the already-committed sea level rise and the sea level rise that could be expected under a range of global warming levels (Seroussi et al. 2020; Goelzer et al. 2020; Edwards et al. 2021; DeConto et al. 2021). Ongoing research to understand how glaciers and ice sheets flow, fracture, and melt in response to climate change aims to narrow this wide range in far-future sea level rise.

Projections of seasonal and extreme precipitation are widely studied and show more consistent and robust responses in extremes than average changes. The physical process link between higher temperatures and higher moisture availability in the atmosphere is well documented and understood. However, uncertainties remain in our understanding of the response of precipitation producing systems, particularly those governed by mesoscale processes such as mesoscale convective systems and thunderstorms, which are not directly simulated in global climate models. Uncertainties, especially around how other factors that influence storm development (such as vertical windshear and atmospheric instability) will change in future climates, link back to model uncertainty and bias at larger scales.

Uncertainty in drought projections arises from these uncertainties in precipitation. Climate models generally project drying in the US Southwest in response to elevated global warming levels, but the precipitation response is highly uncertain. The response of land vegetation also complicates drought projections. Under elevated CO₂ levels, certain types of plants may become more efficient at using water due to a physiological response. This is expected to be at least partially counteracted by greening in response to elevated CO₂ levels. Additionally, the vegetation response to increased heat stress, extreme precipitation, and fire risk is complex and not yet fully understood.

Description of Confidence and Likelihood

There is *very high confidence* that many impacts—both changes to the average state and the risk of extreme events—will intensify as the temperature increases. This is based on physical understanding of the underlying drivers reflected in climate models of varying complexity. There is *very high confidence* (in fact, it is unequivocal) that warming increases with GHG emissions. It is *very likely* that the eventual global warming in response to a doubling of atmospheric CO₂ is between 2.3° and 4.7°C and *likely* that the warming would be between 2.6° and 3.9°C (Sherwood

et al 2020). There is *high confidence* that catastrophic scenarios where warming exceeds 4°C cannot be ruled out.

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1. Overview

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Summary findings in the Overview are drawn from assessment chapters. References to full chapters (e.g., {Ch. 2}) and specific chapter Key Messages (e.g., {2.1}) are indicated in curly brackets.

1	1. Overview	1
2	1. How We Are Addressing Climate Change	4
3	1.1. Every degree counts	4
4	1.2. Innovation has propelled reductions in greenhouse gas emissions	4
5	1.3. Adaptation is moving forward across the country	5
6	1.4. Communities are taking action to strengthen resilience	5
7	Table 1.1. Cities, States, Tribes, and Communities Are Taking Action to Address Climate Change	5
8	1.5. Deep cuts in emissions would be required to meet national commitments	6
9	Figure 1.1. Warming Depends on Future Emissions	7
10	Box 1.1. New Knowledge Is Informing Climate Action	8
11	2. How We Experience Climate Change	9
12	2.1. The changes occurring now are unprecedented in human history and accelerating	10
13	Figure 1.2. Changes in Average Surface Temperature in United States	10
14	Figure 1.3 Current Climate Conditions Are Unprecedented for Thousands of Years	11
15	2.2. Many extreme events are becoming worse	11
16	Figure 1.4. Damages by State from Billion-Dollar Disasters in the United States (2018–2022)	12
17	2.3. Intensifying extremes are more harmful in an interconnected world	13
18	2.4. Climate change exacerbates inequality	13
19	2.5. Every part of the United States is feeling the effects of climate change	14
20	Table 1.2. All Regions Are Experiencing a Mix of Adverse Climate Impacts	15
21	3. The Risks We Are Facing	17
22	3.1. Safe, reliable water supplies are threatened by drought, flooding, and sea level rise	17
23	Figure 1.5.	18
24	3.2. Disruptions to food systems are expected to increase	18
25	Figure 1.6.	19
26	3.3. Homes and property are at risk from more intense extreme events	20
27	Box 1.2. Migration and Displacement	20
28	3.4. Infrastructure and services are increasingly damaged and disrupted by extreme weather	21
29	Figure 1.8.	22
30	3.5. Climate change exacerbates existing health challenges and creates new ones	22
31	Box 1.3. Indigenous Ways of Life and Spiritual Health	23
32	Figure 1.9.	24
33	3.6. Ecosystems are undergoing transformational changes	24
34	Figure 1.10.	25
35	3.7. Climate change slows growth of economies at home and abroad	25
36	Figure 1.11.	26
37	3.8. Regional economies and livelihoods are threatened by damages to natural resources and intensifying extremes	27
38	Figure 1.12.	28
39	3.9. Job opportunities are shifting due to climate change	28
40	Figure 1.13.	29
41	3.10. Climate change is disrupting culture, heritage, and traditions	29
42		

1	Figure 1.14.	30
2	4. Where We Are Headed	31
3	4.1. Societal choices drive greenhouse gas emissions	31
4	Box 1.4. Global Warming Levels	31
5	Figure 1.15. US Warming Depends on How Much Greenhouse Gases We Emit	32
6	4.2. Rising emissions are driving rapid global warming, with regional differences	33
7	Figure 1.16. What would 3.6°F (2°C) of global warming feel like in the United States?	34
8	4.3. Warming increases risks	34
9	Figure 1.17. Consequences Are Greater at Higher Global Warming Levels.....	35
10	5. How We Move Forward	36
11	5.1. Immediate actions have near-term benefits	36
12	Figure 1.18. There Are Many Cost-Effective Options in the United States for Reducing Near-Term Emissions ...	37
13	5.2. Avoiding the worst impacts requires sharply reducing emissions	38
14	5.3. Transformative adaptation reduces unequal vulnerabilities	39
15	Table 1.3. Incremental Versus Transformative Adaptation Approaches	39
16	5.4. Mitigation and adaptation actions result in systemic, cascading benefits	40
17	5.5. Transformative change is an opportunity for a more just Nation	40
18		
19		

1. How We Are Addressing Climate Change

While the effects of human-caused climate change on the United States are already far-reaching and worsening, every additional amount of warming that we avoid or delay will reduce harmful impacts. Communities are now equipped with a stronger understanding of the risks they face and are taking action to limit the causes and harmful consequences of a changing climate. The faster, deeper cuts in greenhouse gas emissions required to reduce the worst harms from climate change are achievable through a rapid transition in how we produce and use energy and manage lands, with cost-effective approaches available today.

1.1. Every degree counts

Every additional increment of warming—and every action to reduce that warming—matters for reducing the harmful impacts of climate change on the United States. Risks from accelerating changes in temperature and precipitation, sea level rise, climate-fueled extreme weather, and other impacts increase further as the planet warms. Each additional increment of warming will cause more damage and greater economic losses than previous warming, while the risk of catastrophic or unforeseen consequences also increases. {2.3, 18.1, 19.1}

More and faster warming increases the risk of infrastructure failure; threats to ecosystems and species that provide food, clean water and air, and other benefits to people; disruption to essential public services; heat-related illness and death and other health impacts; loss of heritage and traditions; declining quality of life; and worsening inequality. {Ch. 8, Ch. 11; 4.2, 5.1, 7.1, 7.2, 9.1, 9.2, 10.1, 10.2, 12.2, 13.1, 14.1, 14.2, 14.3, 14.4, 15.1, 15.2, 16.1, 17.1, 19.1, 19.3}

The faster and further the world cuts greenhouse gas emissions, the less future warming will occur and the safer every American will be from harmful impacts. {2.3}

1.2. Innovation has propelled reductions in greenhouse gas emissions

States, communities, business owners, and organizations across the country are taking steps to reduce emissions. These efforts are supported by rapidly falling costs of low-carbon energy technologies, expanding options for reducing energy demand and using energy efficiently, and the adoption of more sustainable land-management practices. For example, wind and solar energy costs have dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources. {5.3, 12.3, 32.1, 32.2, 32.5; Figure 32.8}

Since 2018, the total number of state-level mitigation activities increased by 83%, and 169 more cities introduced emissions reductions targets. Renewable energy and energy efficiency projects on tribal lands have also expanded. {16.1, 16.3, Figure 16.4, 25.3, 32.5}

As a result of these advances and continued reductions in coal use, US greenhouse gas emissions fell 12% between 2007 and 2019. {32.1}

1.3. Adaptation is moving forward across the country

As more people face more severe climate risks, individuals, organizations, companies, communities, and governments are taking advantage of adaptation opportunities that reduce climate harms. New tools, more data, advancements in social and behavioral sciences, and better consideration of practical experiences are facilitating a range of actions. (see Box 1.1) {12.3; Ch. 31, Introduction}.

For example, state climate assessments and online climate services portals are providing communities with location- and sector-specific information on climate hazards to support adaptation planning and implementation across the country, including: {31.4; Table 31.1}

- Nature-based solutions to reduce shoreline erosion {8.4, 9.3, 21.1}
- Upgrades to stormwater infrastructure that account for heavier rainfall {24.4}
- Innovative agricultural practices to manage increasing drought risk {11.1, 22.4, 25.5}
- Assessment of climate risks to roads and public transit {13.1}
- Vegetation management to reduce wildfire risk {5.3}
- Urban heat planning to reduce health risks from heat extremes {12.3, 21.1}
- Managed retreat from high-risk coastal areas in ways that consider equity {9.3}

1.4. Communities are taking action to strengthen resilience

Actions to address climate change are underway in every region of the country.

Table 1.1. Cities, States, Tribes, and Communities Are Taking Action to Address Climate Change

CAPTION: Examples of local adaptation and mitigation actions around the country.

Region	Action
Northeast	Chelsea, Massachusetts, and New York City distributed air conditioners to low-income residents to reduce the impacts of extreme heat. {21.1}
Southeast	The state of North Carolina funded several measures to reduce flood risk in Princeville, including buyouts, elevating homes, and building replacement housing that meets local flood standards. {Box 22.1}
U.S. Caribbean	Many community-based organizations in Puerto Rico have undertaken actions to advance social transformation, climate adaptation, and sustainable development. {23.5}
Midwest	A project on the inner harbor of Ashtabula, Ohio, used dredged sediment to restore wetlands displaced by shoreline development, improving coastal protection for the port on Lake Erie. {24.4; Figure 24.9}

Northern Great Plains	The Nebraska Natural Resources Conservation Service, in partnership with university researchers, supported farmers in testing soil health and evaluating soil management practices that promote climate adaptation. {25.5; Table 25.1}
Southern Great Plains	Texas-based groups are supporting soil and land management practices that increase carbon storage while protecting and restoring natural ecosystems. {26.2}
Northwest	The Confederated Tribes of the Colville Reservation are prioritizing carbon capture in their forest and timber management efforts, leading to improved air and water quality and wildlife habitat as well as preservation of cultural areas and practices. {27.3}
Southwest	In response to severe drought conditions, the US and Mexican governments, seven Colorado River basin states, and Indigenous peoples are collaborating to improve water conservation and develop adaptation solutions. {28.1; Box 28.1}
Alaska	To address threats to traditional foods, the Chugach Regional Resources Commission is incorporating Indigenous knowledge and western scientific methods in its adaptation efforts, including weekly water sampling for harmful algal blooms and placement of young clams on beaches with dwindling clam populations. {29.8; Box 29.6}
Hawai'i and US-Affiliated Pacific Islands	The Kaua'i Island Utility Cooperative achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours. Kaua'i is projected to achieve a 90% renewable portfolio by 2026. {30.3}

Climate action is an opportunity to address social and environmental injustices that put some communities at greater risk from adverse climate change impacts. Many communities are prioritizing equitable and inclusive planning processes to help ensure that mitigation and adaptation actions don't benefit some at the expense of others. As additional climate actions are implemented, more widespread consideration of their social impact can help inform decisions around how to fairly distribute the outcomes of investments. {12.4, 13.2, 20.6, 21.3, 21.4, 26.4, 27.1, 31.2, 32.4}

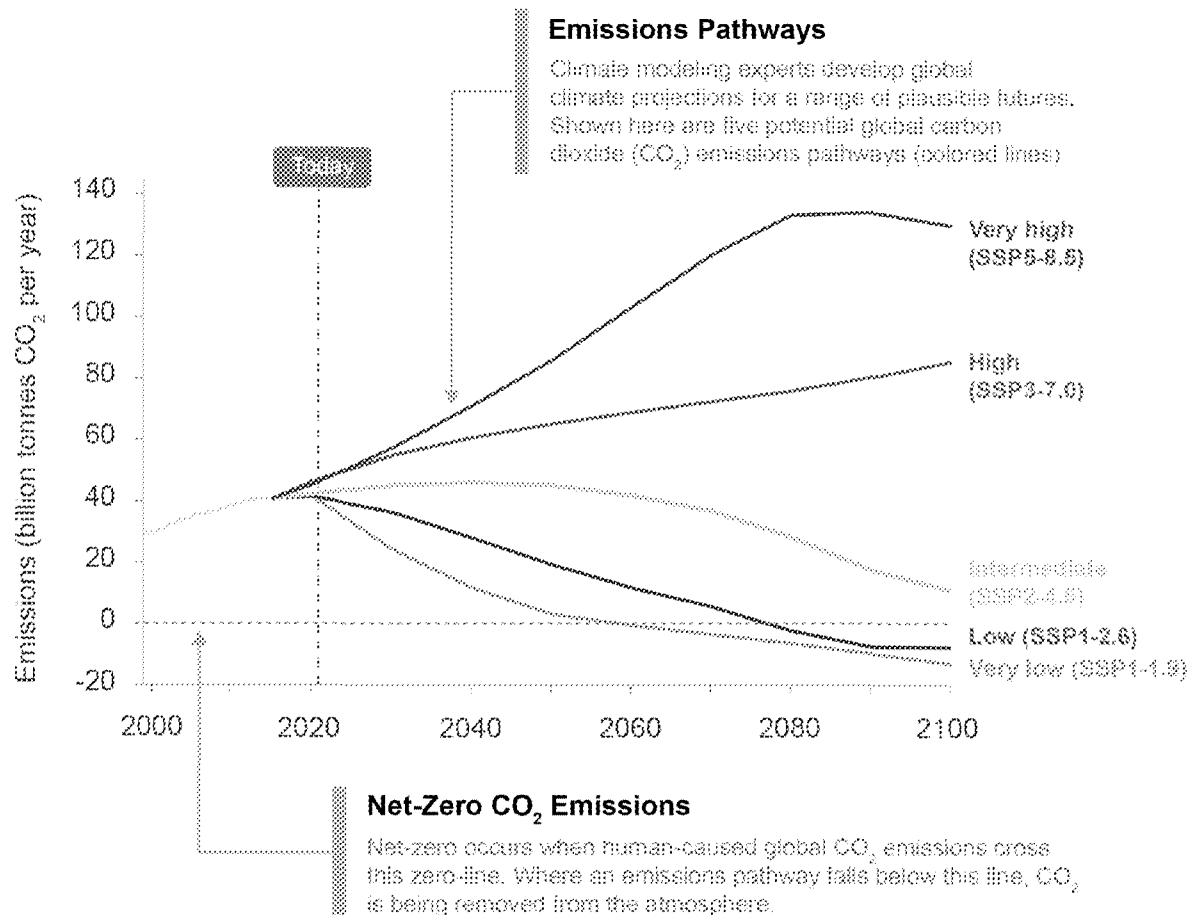
1.5. Deep cuts in emissions would be required to meet national commitments

Atmospheric concentrations of carbon dioxide (CO₂), the primary greenhouse gas produced by human activities, continue to rise due to ongoing growth in global emissions. The world will continue warming until human-caused emissions of long-lived greenhouse gases (primarily CO₂) reach net zero, with some climate changes continuing beyond the time we reach net-zero

emissions. Net zero means that emissions must decline to zero or that any ongoing emissions must be offset by an equivalent removal of greenhouse gases from the atmosphere (Figure 1.1). {2.1, 2.3, 3.1, 32.1}

To achieve current national and international commitments to limit global warming to well below 3.6°F (2°C), and preferably to 2.7°F (1.5°C), compared to the preindustrial era (1850–1900), global CO₂ emissions would have to reach net zero around 2050. {2.3, 32.1}

Figure 1.1. Warming Depends on Future Emissions



CAPTION: The five scenarios shown demonstrate potential climate futures through the end of this century, which are largely determined by how much carbon dioxide humans continue to emit. See Front Matter for scenario definitions. Source: Adapted from Arias et al., 2021.

While US greenhouse gas emissions are decreasing, the current rate of decline is not sufficient to meet current national and international commitments designed to avoid the worst harms from climate change. US emissions remain substantial and would have to decline by more than 6% per

year on average to meet current national goals of reaching net-zero emissions around 2050. {32.1}

Deep emissions cuts over this time frame are achievable with existing technologies and approaches. Many cost-effective options are feasible now that have the potential to substantially reduce emissions over the next decade (see Overview 5.1). Faster and more widespread deployment of renewable energy and other low-carbon energy options would accelerate the transition to a decarbonized US economy and increase our chances of meeting the 2050 national net-zero emissions goal. {5.3, 6.3, 32.2}

Box 1.1. New Knowledge Is Informing Climate Action

Key scientific advances since the publication of the Fourth National Climate Assessment (2018) have improved understanding of the climate system, current and future risks from climate change, and adaptation and mitigation approaches.

Physical Climate Science

- **Reduced uncertainty:** New observations combined with improved climate modeling provide multiple lines of evidence supporting advances in understanding and projections of climate change. Improved understanding has narrowed the estimated range of how much the Earth will warm if CO₂ in the atmosphere doubles from preindustrial levels by 50%, to 4.5°–7.2°F (2.5°–4.0°C). {Ch. 3}
- **Improved attribution:** Scientific advances have increased confidence in the linkages between many weather disasters and climate change. Scientists can now rapidly quantify how much more frequent and/or severe a specific extreme event has become due to human-caused warming. For example, the record-breaking June 2021 heatwave in the Pacific Northwest would have been virtually impossible without it. {Ch. 2, Introduction; 2.2, 3.6}
- **Incorporating socioeconomics:** New model projections are based on scenarios that span a range of future social and economic development pathways. These scenarios allow for a deeper exploration of the interactions between development and emissions pathways. {2.3, 3.4, 6.3, Appendix 3}
- **New models:** The latest generation of Earth system models incorporates more detailed simulations of the physics of the climate system and provides improved understanding of how regional-scale processes will change with warming. {3.4}

Risks to Ecosystems and People

- **Connecting justice:** More information is available on disproportionate climate change impacts on overburdened communities and the intersection of environmental justice and climate change. This includes a better understanding of how climate impacts exacerbate

and are exacerbated by inequality. {4.2, 9.2, 11.2, 12.2, 14.3, 15.2, 16.2, 17.1, 19.1, 20.6, 21.3, 26.4, 27.1}

- **Untangling interconnections:** New evidence, including observations of current impacts and enhanced modeling of future risks and responses, highlights the compounding and cascading effects of climate change on the built environment and interconnected food, energy, and water systems. More information is available on how climate change affects national security, sustainable and equitable development, and disaster risk reduction and recovery. {Chs. 6, 17, 18, and 19; Ch. 28, Introduction; 4.2, 5.1, 12.2}
- **Defining degrees:** Improved understanding of the risks human and environmental systems face under each additional increment of global warming has helped researchers quantify potential damages to health, livelihoods, and the economy. {Ch. 8, Introduction; 19.1}

Responses

- **Sophisticated support:** Improved tools, data, and climate projections needed to support adaptation and management of natural resources and infrastructure are becoming more widely available. This includes advancements in quantifying the range of economic, health, and environmental benefits from mitigation and adaptation actions and better documentation of how benefits and burdens are being distributed. {Ch. 4, Introduction; 5.3, 7.3, 11.3, 12.2, 13.2}
- **Understanding people:** Advances in social sciences are providing insight into how people experience climate change and how adaptation and mitigation actions are understood, communicated, and implemented. Increased documentation of institutional changes, partnerships, inclusive knowledge sharing, and sustainable financing options are helping accelerate climate change planning at multiple levels of government. {12.3, 20.1, 20.4}
- **Practical examples:** More examples of adaptation in practice, such as green infrastructure and nature-based solutions, are now seen across the Nation. Cities and states that have implemented adaptation actions are sharing best practices and aiding cooperation. In addition, many communities are learning from tribal and Indigenous leadership in climate change responses. {Ch. 31, Introduction; 12.3, 16.3}

[END BOX 1.1 HERE]

2. How We Experience Climate Change

Americans are feeling the effects of climate change in their everyday lives, as intensifying extreme events strain public services and outdated infrastructure. As climate risks continue to increase in scale and frequency, multiple climate hazards and cascading climate impacts are disrupting essential societal systems in every part

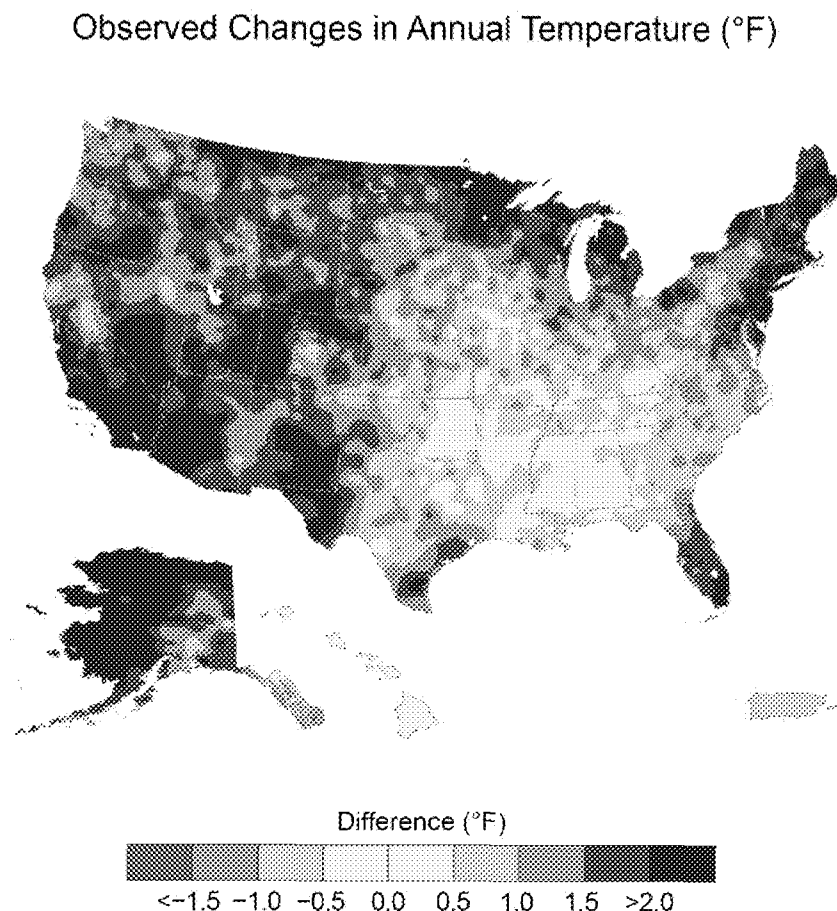
of the country. Communities that are already overburdened experience harmful impacts first and worst, exacerbating existing inequalities.

2.1. The changes occurring now are unprecedented in human history and accelerating

Since the 1970s, there has been a marked acceleration in the cause of climate change (human-caused greenhouse gas emissions) and its effects, including increasing temperatures (Figure 1.2), rising sea levels, melting ice, ocean warming and acidification, changing rainfall patterns, and shifts in timing of seasonal events. Human activities have increased the frequency and intensity of many extreme events, as well as the likelihood of sequential and concurrent extreme events. Many climate conditions and impacts being experienced today are unprecedented for thousands of years (Figure 1.3). {2.1, 2.2, Appendix 4}

These trends are projected to continue over the next decade even if greenhouse gas emissions fall substantially, leaving the country no choice but to adapt to a changing climate. {Ch. 2}

Figure 1.2. Changes in Average Surface Temperature in United States

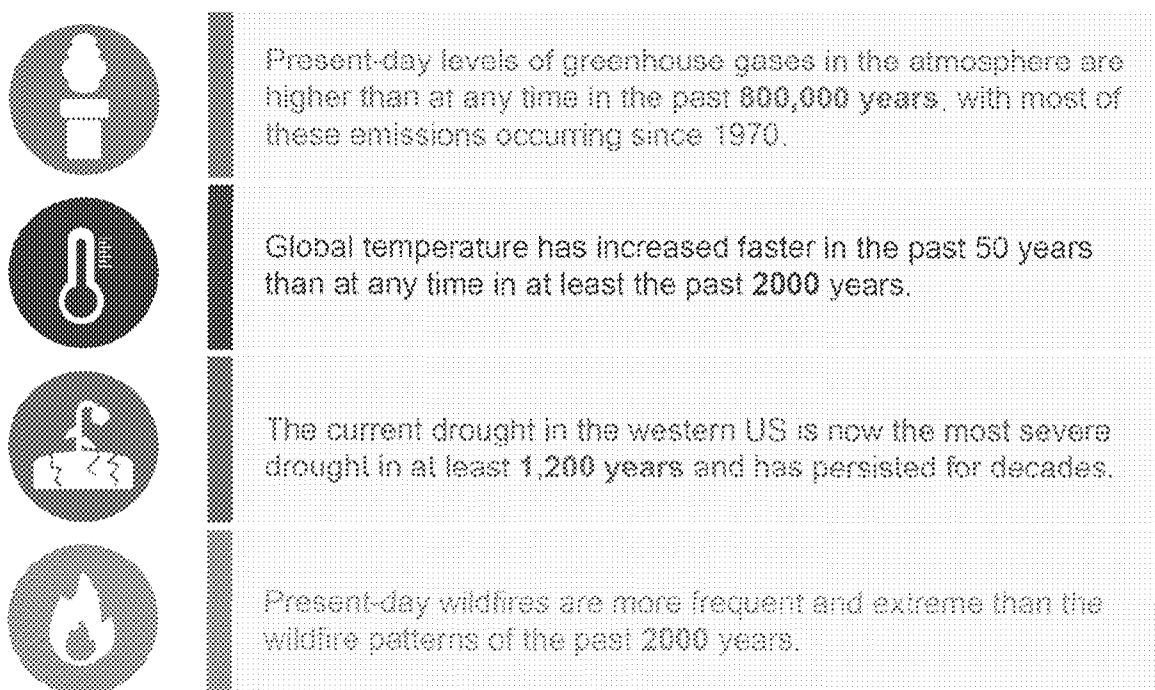


CAPTION: Placeholder for a visualization showing changes in average surface temperature over time in

the United States. Changes shown are the difference between the average for the present day (1992–2021) and the average for the first half of the last century (1901–1960 for the contiguous United States [CONUS], Hawai‘i, and Puerto Rico; 1925–1960 for Alaska). Temperature and precipitation estimates for CONUS and Alaska are derived from the nClimGrid dataset (Vose et al. 2014, 2017). For Hawai‘i and Puerto Rico, temperature estimates are derived from NOAA GlobalTemp (Vose et al. 2021), and precipitation estimates are derived from the Global Precipitation Climatology Center dataset (Becker et al. 2013). Adapted from Figure 2.4.

Figure 1.3 Current Climate Conditions Are Unprecedented for Thousands of Years

Current Climate Conditions Are Unprecedented For Thousands of Years



CAPTION: Many of the accelerating physical climate impacts observed today are unprecedented in human history. {2.1; Focus on Western Wildfires} Source: USGCRP 2023.

2.2. Many extreme events are becoming worse

For many Americans, their primary experience of climate change is through its influence on extreme events. Many extremes, including heatwaves, heavy precipitation, drought, flooding, wildfire, and tropical cyclones/hurricanes, are becoming more frequent and severe due to climate change, with a cascade of effects in every part of the country. {Ch. 2, Introduction; 2.2, 3.6, 3.12, 4.1, 4.2, 7.1, 9.1, App 4}

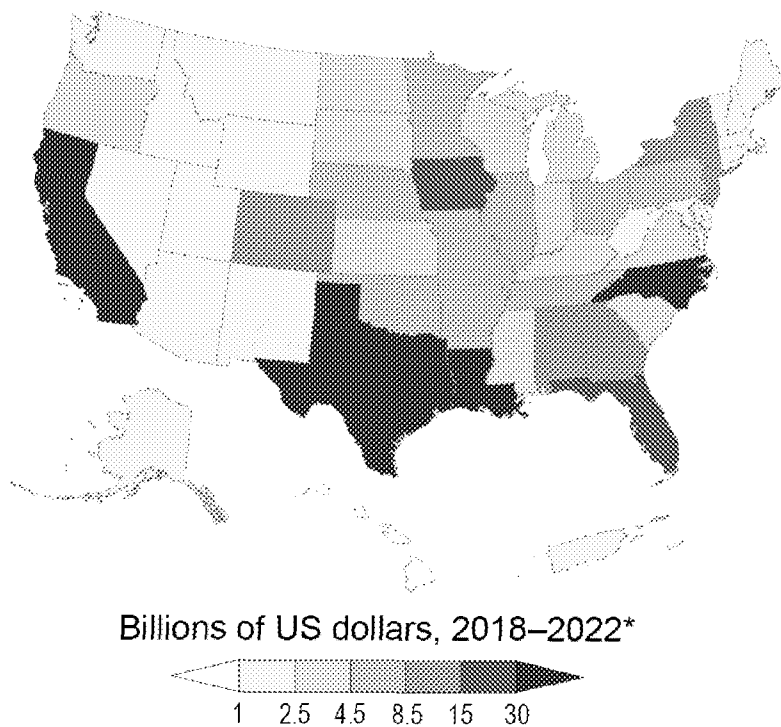
Rising temperatures have increased heat-related illnesses and deaths in many regions of the

United States in recent decades. Extreme heat and wildfire smoke are increasing risks to outdoor workers and jeopardizing participation in outdoor sports and recreation. Cultures, traditions, and livelihoods tied to land, water, and ecosystems are being disrupted by the effects of more severe extremes. {7.1, 10.1, 11.2, 15.1, 16.1, 26.1, 27.6, 29.4; Focus on Western Wildfires; Focus on Compound and Complex Events}

Worsening extreme weather events are causing direct economic losses through infrastructure damage, disruptions in critical services, and losses in property values. Over the past five years, the United States has seen an increase in billion-dollar weather and climate disasters (Figure 1.4). In the 1980s, the country experienced on average one (inflation-adjusted) billion-dollar event every four months. Now, there is one every three weeks on average. {Ch.2, Introduction; 4.2, 19.1}

Figure 1.4. Damages by State from Billion-Dollar Disasters in the United States (2018–2022)

The US now experiences,
on average, a billion-dollar weather
and climate event every three weeks.



CAPTION: Billion-dollar weather and climate disasters are events where overall damages/costs reach or exceed \$1 billion, including adjustments for inflation. Billion-dollar events are increasing in frequency and cost, in part because of human-caused warming. On average, 7.7 billion-dollar events occurred each year between 1980 and 2021. During 2018–2022, 80 [*as of July 2022, to be updated*] such events

affected the United States. The state with the highest costs in this time period was Louisiana, with damages totaling more than \$85 billion. {2.2, Focus on Compound and Complex Events}. Source: *NCEI 2022*

2.3. Intensifying extremes are more harmful in an interconnected world

Compound events—combinations of weather or climate events affecting one location back-to-back or multiple locations at the same time—are already occurring in every region of the country and are projected to become more frequent as the world continues to warm. These events have cascading effects through supply chains, food networks, and other interdependent systems that typically cause greater harm than isolated events. {Focus on Compound and Complex Events, Focus on Risks to Supply Chains}

Experiencing compound events takes a significant toll on the well-being of individuals and communities. More frequent and severe extreme events and other climate risks are already straining emergency response resources and infrastructure, with disproportionate effects on overburdened communities. {15.1, 24.3, 26.5; Focus on Compound and Complex Events, Focus on COVID-19 and Climate Change}

Recent compound events illustrate how impacts can cause cascading failures that intensify harmful impacts on ecosystems and communities. For example, in 2020, record-breaking heat coincided with widespread drought, contributing to concurrent large, destructive fires across California, Oregon, and Washington. These events exposed millions of people to multiple health hazards and stretched fire-fighting resources. Drought persisted into 2021, amplifying the 2021 record-breaking Northwest heatwave, which resulted in more than 229 heat-related fatalities and another severe wildfire season. Compound heat and drought triggered harmful algal blooms and contributed to mass die-offs of shellfish and salmon, species important to the region's Indigenous communities and economy. Together, these events caused damages exceeding \$36 billion [2021]. {Ch. 2, Introduction; Focus on Compound and Complex Events, Focus on Western Wildfire}

2.4. Climate change exacerbates inequality

The effects of climate change are felt most strongly by communities that are already overburdened, including Indigenous peoples, people of color, and low-income communities. These frontline communities experience harmful climate impacts first and worst, yet are often the least responsible for the greenhouse gas emissions that cause climate change. Climate change exacerbates existing risks to these communities from unmet infrastructure needs, low-quality housing, and other stressors, creating a cycle of worsening inequality. {4.2, 9.2, 9.3, 15.2, 16.1, 16.2, 18.2, 19.1, 20.3, 20.6, 21.3, 26.4, 27.2, 31.2}

Historical discriminatory policies such as redlining and displacement of Indigenous peoples forced communities of color into the least-valuable, often low-lying areas that are now more vulnerable to flooding, extreme heat, and air pollution from fossil fuel facilities and industry.

Decades of disinvestment in infrastructure and services in formerly redlined and low-income neighborhoods limits the ability of residents to prepare for and recover from extreme events and other climate stressors. {4.2, 5.2, 9.2, 12.2, 14.3, 15.2, 20.3, 21.3, 22.1, 26.4, 27.2; Ch. 16, Introduction}

Today, formerly redlined and low-income areas tend to have fewer trees, more pavement, and higher levels of air pollution than other neighborhoods, meaning their residents feel the effects of extreme heat more acutely and are more susceptible to adverse health impacts. Low-income neighborhoods, including those historically affected by redlining or other discriminatory policies, can be as much as 12.6°F (7°C) hotter during heatwaves than wealthier neighborhoods. {Ch 2, Introduction; 12.2, 14.3, 15.2, 21.3, 22.2, 27.2}

2.5. Every part of the United States is feeling the effects of climate change

People across the country are facing increasing risks from climate change. These risks will grow through 2030 even if greenhouse gas emissions fall substantially (see Box 1.4). While risks vary by location and community, all regions are feeling some mix of increasingly harmful climate impacts. {Ch. 2, Introduction; Chs. 21–30}

The near-term climate impacts described in Table 1.2 have important social, economic, and health consequences that disproportionately harm frontline communities (see Overview 2.4). The table shows examples of critical impacts affecting people in each region over the next few years—but these damages often cascade through social and ecological systems and across regional borders and may lead to longer-term losses.

How vulnerable any one person is to the impacts of climate change is driven by a complex mix of biological, demographic, social, economic, and political factors that affects their exposure to climate risks, sensitivity to impacts, and capacity to adapt and recover. {15.2; Figure 15.5; Ch. 20, Introduction}

Table 1.2. All Regions Are Experiencing a Mix of Adverse Climate Impacts

CAPTION: Examples of important climate impacts affecting each region between now and 2030. Icons indicate general categories of impacts: infrastructure, water supply, health and well-being, food security, livelihoods and heritage, and ecosystems. More information can be found in the regional chapters (Chs. 21–30) via the Key Message (KM) links shown. Source: USGCRP 2023 (in development—placeholder image of formatted table shown directly below, followed by text table)

(example of formatted table)

Northeast	 Damages to critical transportation, energy, and communications infrastructure increase KM 21.1	 Species range and habitat, especially in the ocean and along coasts, are shifting KM 21.2	 Heritage, livelihoods, and traditions such as winter recreation are threatened KM21.3 and 21.4
Southeast	 Displacement of low-income communities increases risk from environmental hazards KM 22.1 and 22.3	 Extreme heat threatens human health, especially stressing urban communities KM 22.2	 Heavy rain and longer dry spells make water resources unpredictable KM 22.4
US Caribbean	 Agricultural losses, especially from tropical cyclones, threaten food security KM 23.1	 Severe drought leads to large agricultural and economic losses KM 23.3	 Rising heat increases power demand and hurricanes and storms stress power grids KM 23.4
Midwest	 Livelihoods are threatened, especially harming farmers and fishers KM 24.2	 Extreme weather events, like heavy rain and flooding, harm public health KM 24.3	 Changing temperature and rainfall damage aging buildings, homes, and businesses KM 24.4 and 24.5
Northern Great Plains	 Rising temperatures and decreasing snowpack reduce water supply KM 25.1	 Increases in extreme heat, wildfire, and flooding harm physical and mental health KM 25.1 and 25.3	 Livelihoods are at greater risk, especially in agriculture, recreation, and energy jobs KM 25.3
Southern Great Plains	 Drier conditions threaten agriculture and water supplies KM 26.1, 26.3 and 26.5	 Extreme heat and high humidity result in disparate harms to human health KM 26.2 and 26.3	 Multiple stressors and extreme events exacerbate inequities and food insecurity KM 26.4
Northwest	 Less water is available for hydropower, rural communities, and aquatic ecosystems KM 27.1, 27.2, and 27.4	 Frontline communities are endangered by extreme heat and wildfire smoke KM 27.1, 27.3, and 27.5	 Outdoor livelihoods and heritage tied to natural resources are threatened KM 27.1, 27.3, and 27.6
Southwest	 Intensifying drought and decreases in groundwater recharge reduce water supply KM 28.1	 Economic losses increase, especially in agriculture and livestock production KM 28.3	 Extreme heat, wildfire smoke, and coastal flooding harm physical and mental health KM 28.4
Alaska	 Increased damages to water, drainage, and sewage infrastructure KM 29.2 and 29.4	 Subsistence, recreational, and commercial fish catch and productivity are reduced KM 29.3	 The range and habitat of Arctic mammals, seabirds, fish, and vegetation are shifting KM 29.5
Hawaii's and USAPI	 Sea level rise and saltwater intrusion reduce irrigation and drinking water supply KM 30.1	 Damages to the coastal built environment including traditional structures increase KM 30.3	 Risks to unique and biodiverse flora and fauna continue to grow KM 30.4

(plain-text version)

Region	Example Impacts		
Northeast	Damages to critical transportation, energy, and communications infrastructure increase. KM 21.1	Species range and habitat, especially in the ocean and along coasts, are shifting. KM 21.2	Heritage, livelihoods, and traditions such as winter recreation are threatened. KM21.3 and 21.4
Southeast	Displacement of low-income communities increases risk from environmental hazards. KM 22.1 and 22.3	Extreme heat threatens human health, especially stressing urban communities. KM 22.2	Heavy rain and longer dry spells make water resources unpredictable. KM 22.4

US Caribbean	Agricultural losses, especially from tropical cyclones, threaten food security. KM 23.1	Severe drought leads to large agricultural and economic losses. KM 23.3	Rising heat increases power demand and hurricanes and storms stress power grids. KM 23.4
Midwest	Livelihoods are threatened, especially harming farmers and fishers. KM 24.2	Extreme weather events, like heavy rain and flooding, harm public health. KM 24.3	Changing temperatures and rainfall damage aging buildings, homes, and businesses. KM 24.4 and 24.5
Northern Great Plains	Rising temperatures and decreasing snowpack reduce water supply. KM 25.1	Increases in extreme heat, wildfire, and flooding harm physical and mental health. KM 25.1 and 25.3	Livelihoods are at greater risk, especially in agriculture, recreation, and energy jobs. KM 25.3
Southern Great Plains	Drier conditions threaten agriculture and water supplies. KM 26.1, 26.3 and 26.5	Extreme heat and high humidity result in disparate harms to human health. KM 26.2 and 26.3	Multiple stressors and extreme events exacerbate inequities and food insecurity. KM 26.4
Northwest	Less water is available for hydropower, rural communities, and aquatic ecosystems. KM 27.1, 27.2, and 27.4	Frontline communities are endangered by extreme heat and wildfire smoke. KM 27.1, 27.3, and 27.5	Outdoor livelihoods and heritage tied to natural resources are threatened. KM 27.1, 27.3, and 27.6
Southwest	Intensifying drought and decreases in groundwater recharge reduce water supply. KM 28.1	Economic losses increase, especially in agriculture and livestock production. KM 28.3	Extreme heat, wildfire smoke, and coastal flooding harm physical and mental health. KM 28.4
Alaska	Increased damages to water, drainage, and sewage infrastructure. KM 29.2 and 29.4	Subsistence, recreational, and commercial fish catch and productivity are reduced. KM 29.3	The range and habitat of Arctic mammals, seabirds, fish, and vegetation are shifting. KM 29.5
Hawai'i and USAPI	Sea level rise and saltwater intrusion reduce irrigation and drinking water supply. KM 30.1	Damages to the coastal built environment, including traditional structures, increase. KM 30.3	Risks to unique and biodiverse flora and fauna continue to grow. KM 30.4

3. The Risks We Are Facing

The things Americans value most are at risk. More intense extreme events and long-term climate changes make it harder to maintain safe homes and healthy families, reliable public services, a sustainable economy, thriving ecosystems, and strong communities. Many of the harmful impacts that people across the country are already experiencing will worsen as warming increases, and new risks will emerge. The threats to the people and places we love, our livelihoods, and pastimes can be reduced now through proactive, proven efforts to substantially cut emissions and adapt to unavoidable changes in ways that address inequities across the Nation.

3.1. Safe, reliable water supplies are threatened by drought, flooding, and sea level rise

Heavy rainfall and floods are intensifying in some parts of the country while droughts deepen elsewhere (Figure 1.5). Rapid shifts between wet and dry periods pose additional threats to human and natural systems because this variability makes water resources unreliable. {4.1, 4.2, 22.3, 24.5}

More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. Urban and agricultural environments are especially vulnerable to runoff and flooding, which can damage crops and transport debris, fertilizers, chemicals, sewage, and other contaminants that contribute to the development of harmful algal blooms and contaminate drinking water supplies. During 1981–2016, excessive rainfall led to a US maize yield loss comparable to that from extreme drought. Communities of color and lower-income communities experience disproportionate flood impacts, as they are more likely to live in flood zones and have limited adaptive capacity. {2.2, 4.2, 6.1, 9.2, 21.3, 26.4}

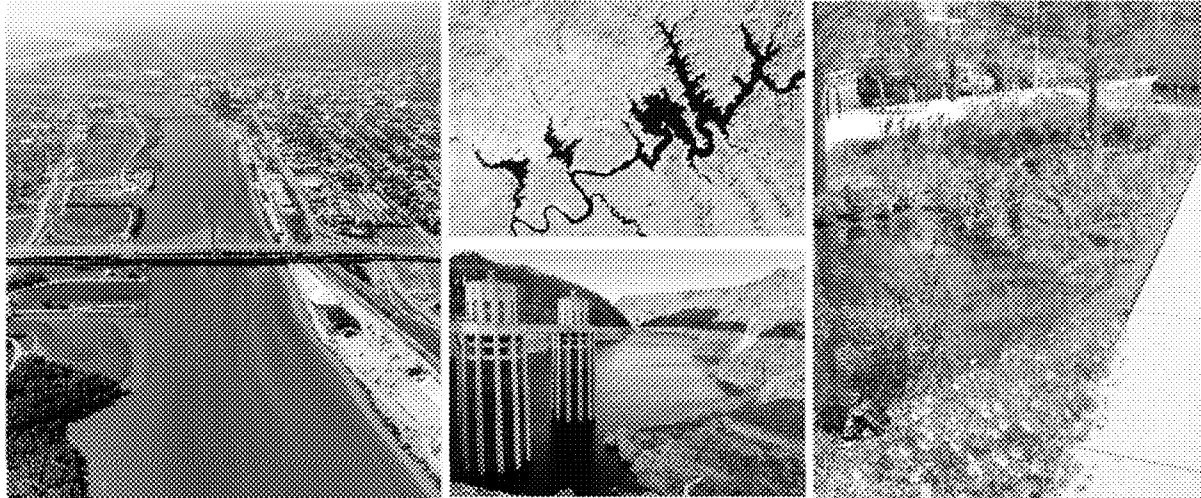
Between 1980 and 2021, drought and related heatwaves across the country caused \$291.1 billion (in 2021 dollars) in damages. Recent droughts have strained surface and groundwater supplies, reduced agricultural productivity, and lowered water levels in major reservoirs, threatening hydropower generation. Aquifers are particularly vulnerable to over-pumping, which could accelerate long-term storage losses. Droughts are projected to increase in intensity, duration, and frequency, most notably in the Southwest, with implications for surface water and groundwater supplies. {2.3, 4.1, 4.2, 5.1, 28.1}

In coastal environments, dry conditions and saltwater intrusion from sea level rise endanger critical groundwater aquifers and stress aquatic ecosystems. Inland, decreasing snowpack alters streamflow, increasing wildfire risk. Small, rural water systems are especially vulnerable because they typically depend on aging infrastructure or a single water source. {4.2, 9.1, 23.3, 27.4, Chs. 7, 22, 24, 25, 26, 27, 28, and 30}

Many proven options are available to protect water supplies, including reservoir optimization, nature-based solutions, and municipal management systems to conserve and reuse water.

Collaboration on flood hazard management at regional scales is particularly important in areas where flood risk is increasing, as cooperation can provide solutions unavailable at local scales {Ch. 4}

Figure 1.5.



CAPTION: (Left, Toledo, OH) Rising temperatures are intensifying harmful algal blooms, which have negative impacts on human and animal health. (Center top and bottom, UT, AZ, NV) Water levels on Lake Powell and Lake Mead have fallen to historic lows in recent years, affecting millions of people across the Southwest. (Right) Rain gardens, a form of green infrastructure, absorb excess stormwater and expand green space. Photo credits: (Left) Zachary Haslick/Aerial Associates Photography Inc., (center top) Lauren Dauphin/NASA Earth Observatory, (center bottom) Vik Friedman/US Department of Energy, (right) Alisha Goldstein/EPA

3.2. Disruptions to food systems are expected to increase

As climate changes, increased instabilities in food production and distribution systems will make food less accessible and more expensive. Projected increases in food prices due to climate change will disproportionately affect the nutrition and health of marginalized groups in both urban and rural areas. Extreme weather effects cascade throughout supply chains by disrupting food production, storage, delivery, and consumption. The impacts of climate change exacerbate economic hardships and disproportionately harm the health of people who are under-resourced or marginalized, such as rural communities, small-scale farmers or fishers, and Indigenous peoples reliant on traditional food sources. Farm workers are disproportionately exposed to unsafe levels of heat, resulting in significantly higher heat-related illness and death rates than among other civilian workers (Figure 1.6). {11.2, Focus on Risks to Supply Chains}

While farmers, ranchers, and fishers have always faced unpredictable weather, climate change heightens threats in many ways:

- Rising CO₂ levels, increasing temperatures, and changes in precipitation reduce productivity, yield, and nutritional content of many crops. These changes can also introduce disease, disrupt pollination, and result in crop failure, outweighing potential benefits of longer growing seasons and increased CO₂ fertilization. {19.1, 21.1, 22.4, 23.3, 24.1}
- Heavy rain and storms damage crops and property and contaminate water supplies. Drought and wildfires reduce forage production and nutritional quality, diminish water supplies, and increase heat stress on livestock. {25.3, 28.3}
- Increasing water temperatures, invasive aquatic species, harmful algal blooms, and ocean acidification and deoxygenation put fisheries at risk. Fishery collapses can result in large economic losses, as well as loss of cultural identity and generational livelihoods. {11.3, 29.4}

In response, farmers and ranchers are adopting innovations in agroecological practices, data-driven precision agriculture, and carbon monitoring. Aquaculture is increasingly seen as a climate-smart approach to increase global protein production, human nutrition, and food security. Tribal food security efforts are helping improve community resiliency to climate change while also improving cultural resiliency {11.1; Box 27.2}

Figure 1.6.

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CAPTION: (Left top, Kenai River, AK) Fishers launching boats during a salmon run. Recent climate extremes have contributed to declines in many salmon populations. (Left bottom, Baltimore, MD) Urban farms provide green space that can help reduce climate impacts like extreme heat and offer other benefits like food production. (Center, Camarillo, CA) Farmworkers are increasingly at risk from intensifying wildfire and extreme heat events during harvest season. (Right top, Malta, MT) Declines in crop yields are anticipated in the Northern Great Plains due to rising temperatures, which increase the potential for pest expansion. (Right bottom, El Campo TX) Rice harvesters worked quickly ahead of hurricane season in July 2020. Photo credits: (left top) Eric Vance/EPA, (left bottom) Preston

Keres/USDA, (center) Andy Holtzman, (right top and bottom) Lance Cheung/USDA.

3.3. Homes and property are at risk from more intense extreme events

Climate change is putting homes, property, and infrastructure at higher risk of damage from more frequent heavy rainfall, flooding, and wildfire, increasing the cost of maintaining a safe and healthy place to live (Figure 1.7). Homes with poor insulation and inefficient heating and cooling systems can make it harder for lower-income households to afford energy bills. People who spend a high percentage of their income on energy costs—such as rural, low-income, and older fixed-income households, communities of color, and renters—are increasingly vulnerable to extreme heat events. For example, Black Americans are more likely than White Americans to live in older, energy-inefficient homes with structural issues, outdated appliances, and faulty energy systems. This disproportionate burden of energy insecurity is associated with higher incidence of poor health outcomes. {Chs. 15 and 22; 22.2, 26.4, 32.4}

Redlining policies, which forced communities of color into the least valuable neighborhoods, systematically deprive low-income neighborhoods of environmental resources like tree cover and access to green spaces (see Overview 2.4). Counties with higher proportions of Black, Hispanic, and Asian residents; people with a high school diploma or less education; and single-parent households are thus often exposed to higher urban heat levels. The same factors that contribute to urban heat islands also increase risks of urban flooding during extreme precipitation events. Climate change is also a risk factor for homelessness, as rising housing costs can result in utility shutoffs and evictions, particularly in subsidized or public housing. {Chs. 12, 22, 27, and 32}

Public cooling centers provide critical health services for those without adequate shelter on hot days. Recent advances are increasing adaptation options, such as hardening homes against weather extremes or relocating, but these options may be out of reach for renters and low-income households without assistance. {15.3, 19.2, 22.2}

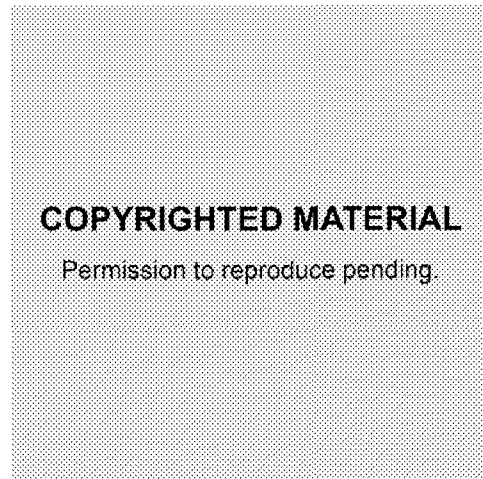
Box 1.2. Migration and Displacement

Historical climate impacts that have shifted where people live include extended drought and major hurricanes. For example, Puerto Rico and the US Virgin Islands were hit by numerous extreme events over the last two decades, driving migration of vulnerable communities to the mainland. In the future, additional climate change impacts—combined with factors like housing affordability, COVID-19, and shifts to teleworking—are expected to increasingly affect migration patterns. More severe wildfires in California, sea level rise in Florida, and more frequent flooding in Texas are expected to displace millions of people, while climate-driven economic changes abroad continue to increase the rate of emigration to the United States. From Northern Alaska to low-lying Pacific atolls, forced migrations and displacements disrupt social networks, decrease housing security, and exacerbate grief, anxiety, and mental health outcomes. Indigenous peoples, who have long faced dispossession of culturally significant lands due to

settler colonialism, are again being confronted with displacement and loss of traditional resources and practices due to climate change. {Chs. 4, 16, 17, 18, 19, 20, 22, 23, 29, and 30}

[END BOX 1.2 HERE]

Figure 1.7.



CAPTION: (Top left, Cedar Rapids, IA) More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. Urban and agricultural areas are especially vulnerable to flooding. (Top right, Loiza, PR) Puerto Rico experienced major impacts from Hurricane Maria in 2017, including damages to coastal infrastructure. (Bottom left, Austin, TX) Icy temperatures and extreme precipitation in February 2020 left communities in Austin, TX, without power and water. (Bottom right, San Francisco, CA) Intense wildfire in September 2020 destroyed towns and resulted in widespread harmful air quality days across the western US. Photo credits: (top left) Don Becker/USGS, (top right), Preston Keres/USDA, (bottom left) Montinique Monroe/Getty Images, (bottom right) Aaron Maizlish.

3.4. Infrastructure and services are increasingly damaged and disrupted by extreme weather

Climate change, particularly the increase in extreme events, increases the probability and frequency of disruptions in vital infrastructure that moves people and goods, powers homes and businesses, and delivers essential public services (Figure 1.8). Risks to energy, water, healthcare, transportation, telecommunications, wastewater, stormwater, and solid waste management systems will continue to rise with further climate change. Many infrastructure systems across the country are at the end of their intended useful life and are not designed to cope with additional stress due to climate change. {Chs. 2, 4, 5, 12, 13, and 15; Focus on Risks to Supply Chains}

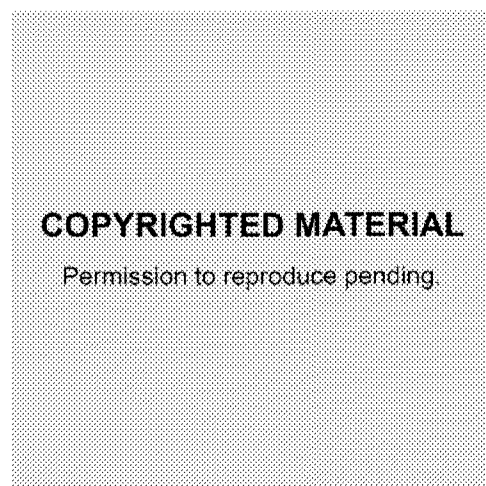
In coastal communities, sea level rise and associated impacts such as flooding and saltwater intrusion are anticipated to severely impact infrastructure, communities, and natural resources, with inequities in how these impacts are experienced. More frequent and intense storms affecting

coastal facilities are expected to cause increased interruption in access to medical care, as seen after Hurricanes Irma and Maria in the US Virgin Islands and Puerto Rico. {9.2, 23.1; Chs. 28 and 30}

At the same time, climate change is expected to increase demands on critical infrastructure. Future increases in average temperatures and more intense heatwaves will heighten electricity and water demand, while wetter storms and more frequent hurricane damages strain wastewater and stormwater pumps. Demand for healthcare is also expected to increase as communities experience higher temperatures and other effects of climate hazards, such as greater exposure to stormwater or wastewater. {Chs. 23 and 30}

Forward-looking designs of infrastructure and related systems can maximize resilience to climate change and provide other benefits, including meeting evolving standards to protect public health, safety, and welfare. Mitigation and adaptation activities are advancing from planning stages to deployment in many areas. These actions range from upgraded grid design and workforce training for electrification to building upgrades and land-use choices. {12.3; Chs. 5 and 13}

Figure 1.8.



CAPTION: (Left, OR) The Hooskanadan Landslide, triggered by heavy rainfall, caused substantial road damage. (Center, Seattle, WA) Internet infrastructure in the greater Seattle area is at risk of inundation from sea level rise by the 2030s. (Right, Maunabo, Puerto Rico) Damages to Punta Tuna Wetlands Nature Reserve from Hurricane Maria, which serves as a buffer against extreme events. Source: (Left) Oregon Department of Transportation; (Center) Art Wager/Getty; (Right) Kenneth Wilsey/FEMA.

3.5. Climate change exacerbates existing health challenges and creates new ones

One of those most direct and devastating ways that Americans are already experiencing climate change is through adverse impacts on health (Figure 1.9). Climate change harms the well-being

of families and communities across the country, with more people exposed to a compounding mix of health hazards, including:

- More severe and frequent extreme events {2.2, 15.1}
- Wider distribution of infectious and vector-borne pathogens {15.1}
- Air quality worsened by smog, wildfire smoke, and increased pollen {Ch. 14}
- Threats to food and water security {11.2, 15.1}
- Mental and spiritual health stressors {15.1}

While climate change harms everyone's health, impacts exacerbate long-standing disparities that result in inequitable health outcomes for historically marginalized people, including people of color, Indigenous peoples, low-income communities, and sexual and gender minorities. Older adults, people with disabilities or chronic diseases, outdoor workers, and children are also disproportionately harmed. {15.2}

The disproportionate health impacts of climate change compound with similar disparities in other health impacts. For example, COVID-19 cases, hospitalizations, and death rates were higher for American Indian and Native Alaskan populations, Pacific Islanders, and Black and Latino Americans than for White Americans. {Focus on COVID-19 and Climate Change, Focus on Western Wildfires}

Reducing greenhouse gas emissions would result in widespread health benefits and avoided death or illness that far outweigh costs (see Overview 5.4). Improving early warning, surveillance, and communication of health threats; strengthening the resilience of healthcare systems; and supporting community-driven adaptation strategies can reduce inequalities in the distribution of resources and capacity needed to adapt as the health threats from climate change continue to grow. {14.5, 15.3, 30.2}

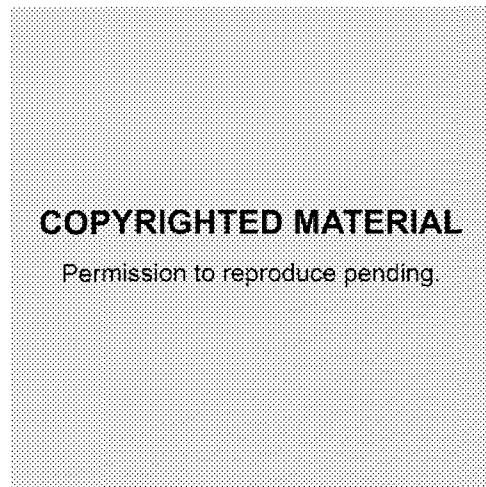
Box 1.3. Indigenous Ways of Life and Spiritual Health

Indigenous communities, whose ways of life, cultures, intergenerational continuity, and spiritual health are tied to nature and the environment, are experiencing disproportionate health impacts of climate change. Rising temperatures and increasingly extreme events are reducing biodiversity and shifting the ranges of culturally important species like Pacific salmon, wild rice, and moose, making it difficult for Indigenous peoples to fish, hunt, and gather traditional and subsistence resources within tribal jurisdictions. Heatwaves can prevent tribal members from participating in tribal ceremonies, while flooding, landslides, and wildfires increasingly disrupt or damage burial grounds and ceremonial sites. {16.1, 15.2, 27.6}

Indigenous peoples have led a number of actions in response to climate change, ranging from planning and policy initiatives to youth movements and cross-community collaborative efforts. Many of these efforts involve planning processes that start with place-based Indigenous knowledge of local climate and ecosystems. {16.3}

[END BOX 1.3 HERE]

Figure 1.9.



CAPTION: (Top left, AZ) The 2021 Telegraph Fire rages through the night; the effects of more severe wildfires on air quality are causing many adverse health impacts (Top right, Alanta, GA) Heatwaves in the Southeast are happening more frequently. Park amenities, such as trees and splash pads, help cool people on hot days. (Bottom left, Charleston, SC) A medical patient crosses floodwaters. (Bottom right, AK). The Dena'ina Athabascan people have lived in the Lake Clark region for thousands of years and depend on subsistence hunting, fishing, and gathering. Photo credits: (top left) Andrew Avitt/USDA-FS, (top right) ucumari photography/Flickr, (bottom left) Grace Beahm Alford/Post and Courier, (bottom right) National Park Service.

3.6. Ecosystems are undergoing transformational changes

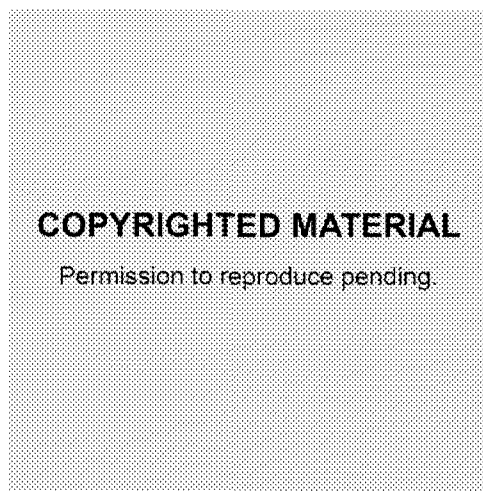
Climate change harms the health of ecosystems, reducing biodiversity and benefits to people. Increasing land and water temperatures continue to reduce habitat ranges and drive migration of plant, bird, and fish species northward or to higher elevations, shifting where residents hunt, catch, or gather economically important and traditional food sources. Extinction of local flora and fauna in vulnerable ecosystems like coral reefs and montane rainforests may occur in the near term, especially where accelerating damages from extreme weather events increase susceptibility to pests and pathogens. Without emissions reductions, drastic changes to ecosystems are expected to pass a tipping point by mid- to late century, where rapid shifts in environmental conditions lead to irreversible ecological transformations. {Chs. 8, 10, 22, 24, 28, 29, and 30}

Many climate impacts, particularly changes in ocean conditions and extreme events, already threaten coastal, and aquatic, and marine ecosystems (Figure 1.10). Hurricanes and storm surge batter mangrove forests and wetlands that protect coastal communities; land-use changes and wildfires harm the water quality of lakes and streams; sea level rise and marine heatwaves decimate the seagrass beds and coral reefs that support key fisheries. Risks to ecosystems and the

people who depend on them are expected to increase with further climate change. For example, mass fish die-offs from extreme summertime heat are projected to double by midcentury in northern temperate lakes. Increases in the frequency and severity of drought, flooding, and wildfire are projected to exacerbate runoff and erosion, promote harmful algal blooms, and expand the range of invasive species. {Chs. 4, 21, 23, 24, 26, 27, 28, and 30}

While adaptation options to protect fragile ecosystems may be limited, management and restoration measures can reduce stress on ecological systems and build resilience. These measures include proactive recovery planning for vulnerable species and protection of essential habitats, such as ecosystem connectors or places where species can avoid heat. {Chs. 8, 23, and 27}

Figure 1.10.



CAPTION: (Top left, CA) Firefighters respond to the 2021 Dixie Fire, which burned almost a billion acres of land. (Top center, Mt. Evans, CO) Mountain goats face habitat loss as high elevation snowfall diminishes. (Top right) Tunnels created by the larvae of bark beetles, which are causing higher damages to US forests as warming and drought intensify. (Bottom left, MI) Whooping cranes and sandhill cranes have faced prey loss due to flooding, drought, and upstream water use. (Bottom right) Coral reef restoration around Florida Keys National Marine Sanctuary. Photo credits: (top left) CAL FIRE, (top center) USFWS, (top right) Cbarlow/Wikimedia Commons, (bottom left) Jim Hudgins/USFWS, (bottom right) Mitchell Tartt/NOAA.

3.7. Climate change slows growth of economies at home and abroad

With every additional increment of global warming, costly damages are expected to accelerate. These costs pose significant risks to the US economy at multiple scales and compound to dampen economic growth (Figure 1.11). {19.1}

- International impacts threaten US economic interests, with climate change projected to reduce midcentury global economic output by 11%–14% (about \$23 trillion). {17.3}

- Economic losses stem largely from extreme events that cost the United States close to \$150 billion (in June 2022 dollars) each year, nearly half the global losses from weather-related events reported in 2021. {17.3, 19.1}
- States, cities, and municipalities confront climate-driven pressures on public budgets and borrowing costs amid spending increases on healthcare and disaster relief. {19.2}
- Household consumers face more expensive goods and services, like groceries and health insurance premiums, as prices change to reflect both current and projected damages. {19.2}

Mitigation and adaptation actions present promising economic opportunities but are not without risk. Public and private measures—such as climate financial risk disclosures, carbon offset credit markets, and investments in green bonds—not only avoid economic losses but improve property values, resilience, and equity. As innovation and trade open further investment opportunities in renewable energy and the country continues to transition away from fossil fuels, loss and disposal costs of stranded capital assets such as coal mines, oil and gas wells, and outdated power plants are expected. {Ch. 19; 17.3}

Figure 1.11.

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CAPTION: (Left, Lewiston, Idaho) Supply chain disruptions are projected to make food less accessible and more expensive. (Center, Savannah, GA), Flooding at ports and transportation hubs impacts the movement of goods. (Right, New York, NY) Hurricanes across the Atlantic seaboard cause major economic disruption. Photo credits: (left) Kirsten Strough/USDA, (center) Preston Keres/USDA, (right) Allison Joyce/Stringer/Getty.

3.8. Regional economies and livelihoods are threatened by damages to natural resources and intensifying extremes

Climate change is projected to reduce US economic output and labor productivity across many sectors, with effects differing based on local climate and the industries unique to each region. Climate-driven damages to local economies especially disrupt heritage industries (such as fishing traditions or trades passed down over generations and cultural heritage-based tourism) and communities whose livelihoods depend on natural resources (Figure 1.12). {Ch. 19}

- As fish stocks in the Northeast move northward and to deeper waters in response to rapidly rising ocean temperatures, important fisheries like scallops, shrimp, and cod are at risk of collapse. In Alaska, climate change has already played a role in 14 major fishery disasters caused by diminished fish catch and severe economic damages. These events were especially damaging for coastal Indigenous peoples, subsistence fishers, and rural communities. {10.2, 21.2, 29.4}
- While the Southeast and US Caribbean face high costs from projected labor losses and heat health risks to outdoor workers, small businesses are already confronting higher costs of goods and services and potential closures as they struggle to recover from the effects of compounding extreme weather events. {22.3, 23.1}
- Agricultural losses in the Midwest, including lower corn yields and damages to specialty crops like apples, are linked to rapid shifts between wet and dry conditions and stresses from climate-induced increases in pests and pathogens. Increasingly frequent and severe wildfire and drought in the Southwest threaten agricultural worker health, reduce cattle production, and devastate wineries. {24.1, 28.1}
- Energy-related livelihoods in the Northern and Southern Great Plains will shift as the demand for renewable energy continues to rise, fossil fuel extraction contracts further, and power infrastructure is increasingly threatened by extreme temperatures and wildfire. {25.3, 26.2}
- Outdoor-dependent industries, such as tourism in Hawai'i and the US-Affiliated Pacific Islands and skiing in the Northwest, are at risk of significant economic loss as continued warming leads to deterioration of ecosystems and coastal infrastructure. {27.3, 30.3}

Larger industries have begun efforts to reduce their greenhouse gas emissions and report climate-related risks and management strategies in response to investor pressure. However, many small businesses will struggle to build or strengthen resilience against projected climate damages, as they tend to have fewer resources and less capacity to develop pre-disaster plans. {Chs. 19 and 22; 26.2}

1 **Figure 1.12.**



2
 3 CAPTION: (Left, CO) Snow-based recreational industries, such as skiing in Colorado, have already lost
 4 revenue due to declining snowfall. (Center, Deer Island, ME) A causeway, and the only road, connecting
 5 Little Deer Isle, ME, to the largest lobster port in the state. (Right, Bloomington, TX) Farm fields
 6 saturated with days of heavy rain. Parts of the United States will experience an increase in extreme
 7 precipitation but decreases in annual average precipitation in the same location. Photo credits: (left)
 8 THEPALMER/Getty, (center) ©Jack Sullivan/Island Institute, (right) Lance Cheung/USDA.

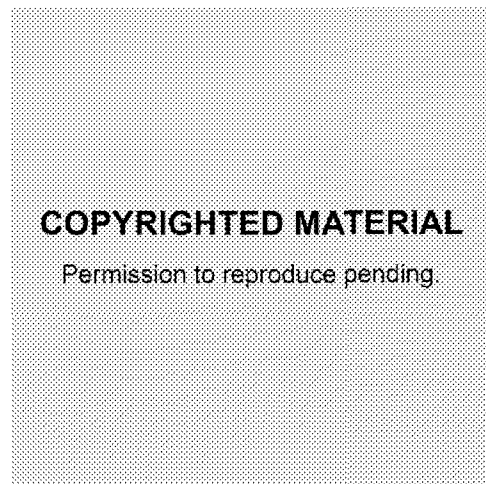
9 **3.9. Job opportunities are shifting due to climate change**

10 Many American households are already feeling the economic impacts of climate change.
 11 Projected economic damages in a warmer world mean that household incomes will be slower to
 12 grow at the same time healthcare, food, insurance, building, and repair costs become more
 13 expensive. Americans' quality of life is also threatened by climate change in ways that may be
 14 more difficult to quantify or predict, such as increased crime and domestic violence, harm to
 15 mental health, reduced happiness, and fewer opportunities for outdoor recreation and play. These
 16 compounding stressors can increase segregation, reliance on social safety net programs, and
 17 income inequality. {19.2; Ch. 11, Introduction}

18 Climate change, and how the country responds, is expected to alter demand for workers and shift
 19 where safe jobs are available (Figure 1.13). Losses in fossil fuel-related jobs will be offset by
 20 increases in mitigation-related jobs, as increased demand for renewable energy and low-carbon
 21 technologies is expected to lead to long-term expansion in most states' energy and
 22 decarbonization workforce. Employment in the renewables sector is already growing in places
 23 like Nevada and Vermont, where grid expansion and energy efficiency efforts are creating new
 24 jobs, and in rural communities where advancements in biofuels and agrivoltaics (combined
 25 renewable energy and agriculture) provide economic opportunities. Additional opportunities

include jobs in ecosystem restoration and construction of energy-efficient and climate-resilient housing, transportation, and water infrastructure. Workforce training and equitable access to clean energy jobs, which to date have tended to exclude women and people of color, are essential for ensuring the transition of displaced coal, oil, and gas workers is just. {5.3, 10.2, 11.3, 13.2, 19.2, 20.6, 22.3, 25.3, 26.2, 27.3, 29.4, 32.4}

Figure 1.13.



CAPTION: (Top; Golden, CO) Solar panels on the campus of the National Renewable Energy Laboratory. (Bottom left; San Antonio, TX) Participants in the 2022 Collegiate Wind Competition, which focused on offshore wind projects. (Bottom right; Lexington, VA) Installing fiber-optic cables. Rural broadband deployment is associated with higher incomes and lower unemployment rates. Photo credits: (top) Werner Slocum/NREL, (bottom left) Werner Slocum/NREL, (bottom right) Preston Keres/USDA.

3.10. Climate change is disrupting culture, heritage, and traditions

As climate change threatens deep-rooted community ties, favorite pastimes, and cherished landscapes, Americans are losing the things that make them feel at home (Figure 1.14). Cultural heritage—including buildings, monuments, livelihoods, practices, art, and music—is at risk, particularly from impacts on natural ecosystems. Damages to archaeological, cultural, and historical sites further reduce opportunities to transfer important knowledge and identity to future generations. {7.2, 9.2, 10.2, 22.1, 23.1, 26.1, 27.6, 30.5; Ch.8; Ch. 10, Introduction; Ch. 30, Box 30.2}

Many beloved sports and outdoor activities are already being affected by climate change, with overall impacts projected to further hinder recreation, tourism, and the ability of communities to maintain a sense of place and heritage {19.1, 24.5, 26.3, 27.6}.

- Significant economic losses are projected from declines in winter sports like skiing, snowshoeing, and snowmobiling as rising temperatures lead to shorter seasons and less snowfall. {25.3, 27.3}

- More frequent and severe heatwaves will make it less safe for athletes and spectators to participate in outdoor sporting events. {26.3}
- Hikers, campers, and cyclists face increasing threats from more severe wildfires and floods and greater exposure to disease-carrying ticks and mosquitoes. {27.6}
- Projected increases in wildfires and worsened air quality make it harder to enjoy the physical and mental benefits of outdoor exercise like walking, jogging, or playing in the park. {27.6}
- Warming waters are increasing the prevalence of invasive species and harmful algal blooms, threatening coastal activities like swimming along beaches in the Southeast, boating and fishing for walleye in the Great Lakes, and viewing whooping cranes along the Gulf Coast. {24.2}
- Tourism industries and local businesses that support recreation are projected to see a rise in park closures, lost revenue, and reductions in workforce. {10.2, 16.1, 25.3, 26.3}

Cost-effective nature-based solutions and ecosystem restoration can preserve cultural heritage while providing valuable local benefits, such as flood protection and new recreational opportunities. Incorporating local values, Indigenous knowledge, and equity into design and planning can help reaffirm a community's connection to place, strengthen social networks, and build new traditions. {7.3, 26.1, 26.3, 30.1, 30.3}

Figure 1.14.

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CAPTION: (Top left, St. Simons, GA) Climate-driven ecosystem changes negatively impact recreational fishing. (Bottom left, Glacier National Park, MT) Wildfire smoke jeopardizes participation in outdoor sports and recreation. (Center, PR) Park rangers working to reopen El Yunque National Forest to visitors after Hurricane Maria. (Top right, Washington, DC) A snowball fight in Lincoln Park. Winter recreation is threatened by warming temperatures. (Bottom right, Capers Island, SC) Rising sea levels have resulted in ghost forests, with implications for coastal recreation. Photo credit: (top left) Ralph Daily/Flickr, (bottom left) Andrew Parlette/Flickr, (center) Preston Keres/USDA, (top right) Brett David/Flickr, (bottom right)

NOAA.

4. Where We Are Headed

Each additional increment of global warming leads to greater risks. The extent of global warming and when society experiences each level of warming is largely dependent on choices made today. The faster and further we cut greenhouse gas emissions, the more we will reduce risks to current and future generations.

4.1. Societal choices drive greenhouse gas emissions

Humans have produced enough greenhouse gases to increase the concentration of CO₂ in the atmosphere by more than 47% since 1850, primarily by using fossil fuels for energy and transportation, as well as from agriculture, deforestation, and manufacturing. These concentrations would have been much higher without the ocean and land carbon sinks, which have removed more than half the CO₂ emitted by human activities. {Ch. 2, Introduction; Figure 3.9; 6.1, 7.2}

The choices we make on a day-to-day basis—how we power our homes and businesses, get around, and produce food and other goods—collectively determine the amount of greenhouse gases emitted. Since 2003, the United States has been the second highest emitter of any country. The US is also the largest contributor to past emissions, which continue to affect the climate. US greenhouse gas emissions are driven by trends in economic growth, population dynamics, energy demand and supply, governance, technology, and globalization. Over the last decade, US emissions have declined while the economy has continued to grow (see Overview 1.5). The choices the United States and other countries make now will determine the trajectory of climate impacts for many generations to come (Figure 1.15) {2.1, 5.2, 16.1; Chs. 2, 16, 20, 32}

Box 1.4. Global Warming Levels

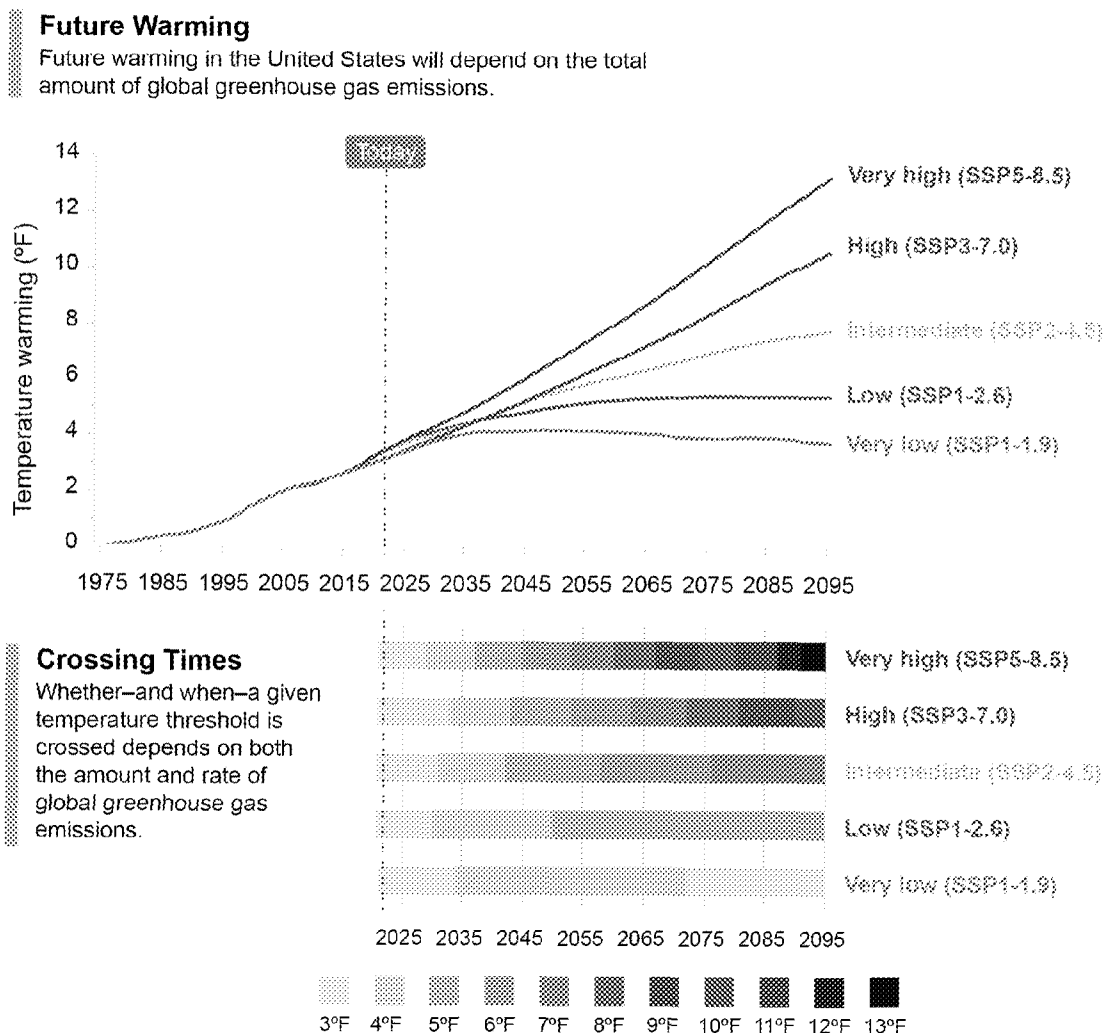
Scientists can't perfectly predict future human actions, so climate models use different scenarios of plausible futures to represent a range of possible emissions trajectories. Future climate change under a given scenario is often expressed in two ways: as a range of potential outcomes in a future year (as in Figure 1.15a), or as a year in which a specific outcome is expected to occur (as in Figure 1.15b).

Over the next decade, projected global warming is very similar across all scenarios. This is due to how long it takes to update infrastructure or make systemic economic and political change, not because the planet is already committed to future warming as a result of past emissions. Only a limited amount of additional warming is projected to occur once net human-caused emissions fall to zero, though some climate changes like increasing ocean heat content and sea level rise will continue even after we reach net-zero emissions (see Overview 1.5). {2.3}

By midcentury (2040–2070), differences between projected temperatures under higher and lower scenarios are apparent. By the end of the century, the global warming level—that is, how much the global average surface temperature increases above preindustrial levels—will likely exceed 5.4°F (3°C) in the high and very high scenarios, and the world could see more than 7.2° (4°C) of warming in the very high scenario. Projected long-term global warming is very likely to be higher than 3.6°F (2°C) in all but the very lowest scenario, which limits warming to 2.7°F (1.5°C). {2.3}

The risk of exceeding a particular global warming level depends on future emissions. This means that future projections are conditional: when or if we reach a particular level of warming is largely dependent on human choices. {2.3}

Figure 1.15. US Warming Depends on How Much Greenhouse Gases We Emit



CAPTION: How much warming the United States will experience—and when a given temperature threshold is crossed—depends on future emissions. The top graph (a) shows projected change in surface temperature from the preindustrial era (1850–1900) in the US (annually averaged over all 50 states and

Puerto Rico) under different scenarios (known as SSPs, or Shared Socioeconomic Pathways; see Front Matter, Table 3). The bottom graph (b) shows the same projections in a different way, highlighting the year in which the US crosses temperature thresholds under each scenario. Source: *USGCRP 2023*

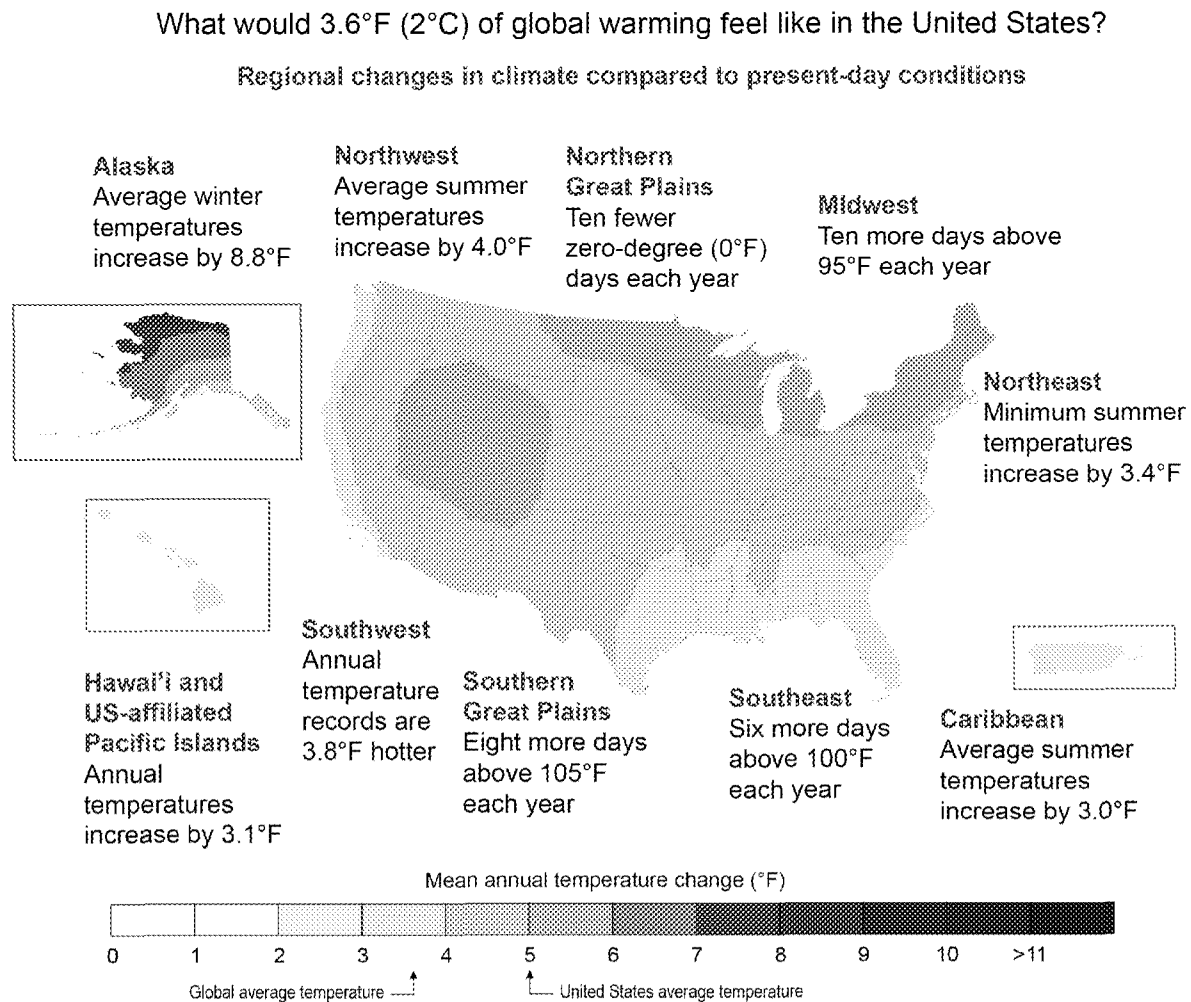
[END BOX 1.4 HERE]

4.2. Rising emissions are driving rapid global warming, with regional differences

Human-driven greenhouse gas emissions have caused nearly all global warming observed since the late 1800s, with only very small effects from natural sources. Global average temperatures over the past decade were approximately 2.2°F (1.2°C) warmer than the preindustrial period (1850–1900), with about three quarters of both the cause (emissions) and the effect (warming) observed since 1970. {2.1, 3.1}

There is incontrovertible evidence of this warming in almost every corner of the world, with many documented indicators of change across the Nation. However, these changes are not happening uniformly. Over the past fifty years, the US has warmed about 68% faster than the planet as a whole, reflecting a broader global pattern in which land areas are warming faster than the ocean and higher latitudes are warming faster than lower latitudes (Figure 1.16). {2.1, 3.3; Ch. 2, Introduction; Appendix 4}

1 **Figure 1.16. What would 3.6°F (2°C) of global warming feel like in the United States?**



2

3 CAPTION: As the world warms, the United States warms more. The map shows projected annual surface

4 temperature changes in the US from present day (1990–2020) under 3.6°F (2°C) of global warming

5 above preindustrial levels (see Figure 2.8). Regional examples demonstrate differences in how

6 temperature impacts are experienced by people across the country. Source: USGCRP 2023

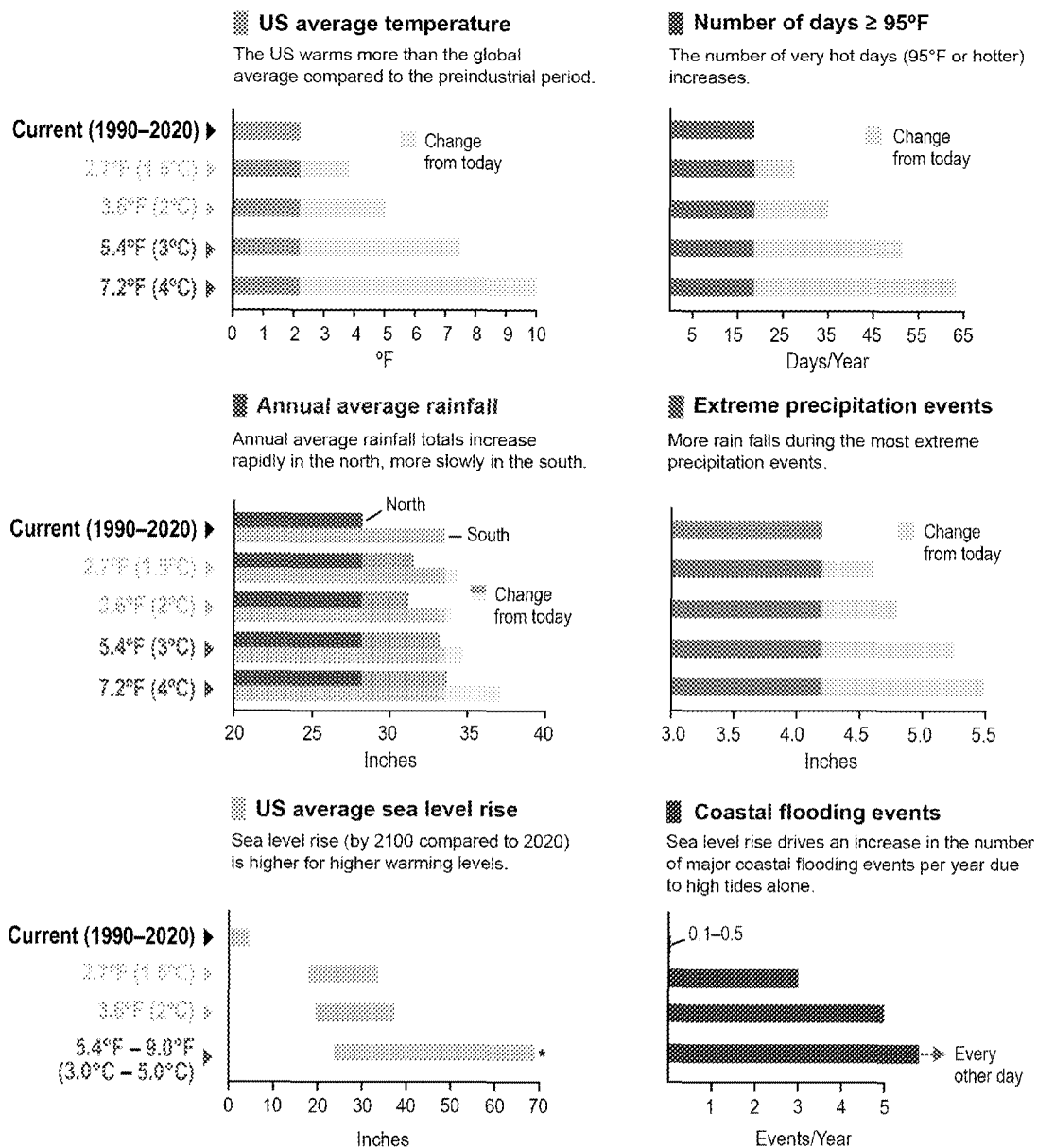
7 **4.3. Warming increases risks**

8 Rising temperatures lead to many other large-scale changes in Earth's climate system, and the

9 consequences will become greater at higher global warming levels (Figure 1.17).

1 Figure 1.17. Consequences Are Greater at Higher Global Warming Levels

Consequences are greater at higher global warming levels.



*Rise at the upper end of this range cannot be ruled out due to the possibility for rapid ice-sheet loss. The amount of warming required to trigger such loss is not currently known, but is assessed to be above 2°C.

CAPTION: With each additional increment of global warming, impacts in the United States are more severe. Temperature (averages and heatwaves; top) and extreme rainfall projections (middle, right) are averages for all 50 states and Puerto Rico. Average rainfall projections (middle, left) are shown for both the northern US (above 37 degrees latitude) and the southern US (below 37 degrees latitude). Global warming levels refer to warming since the preindustrial period, defined as 1850–1900. Source: USGCRP 2023.

5. How We Move Forward

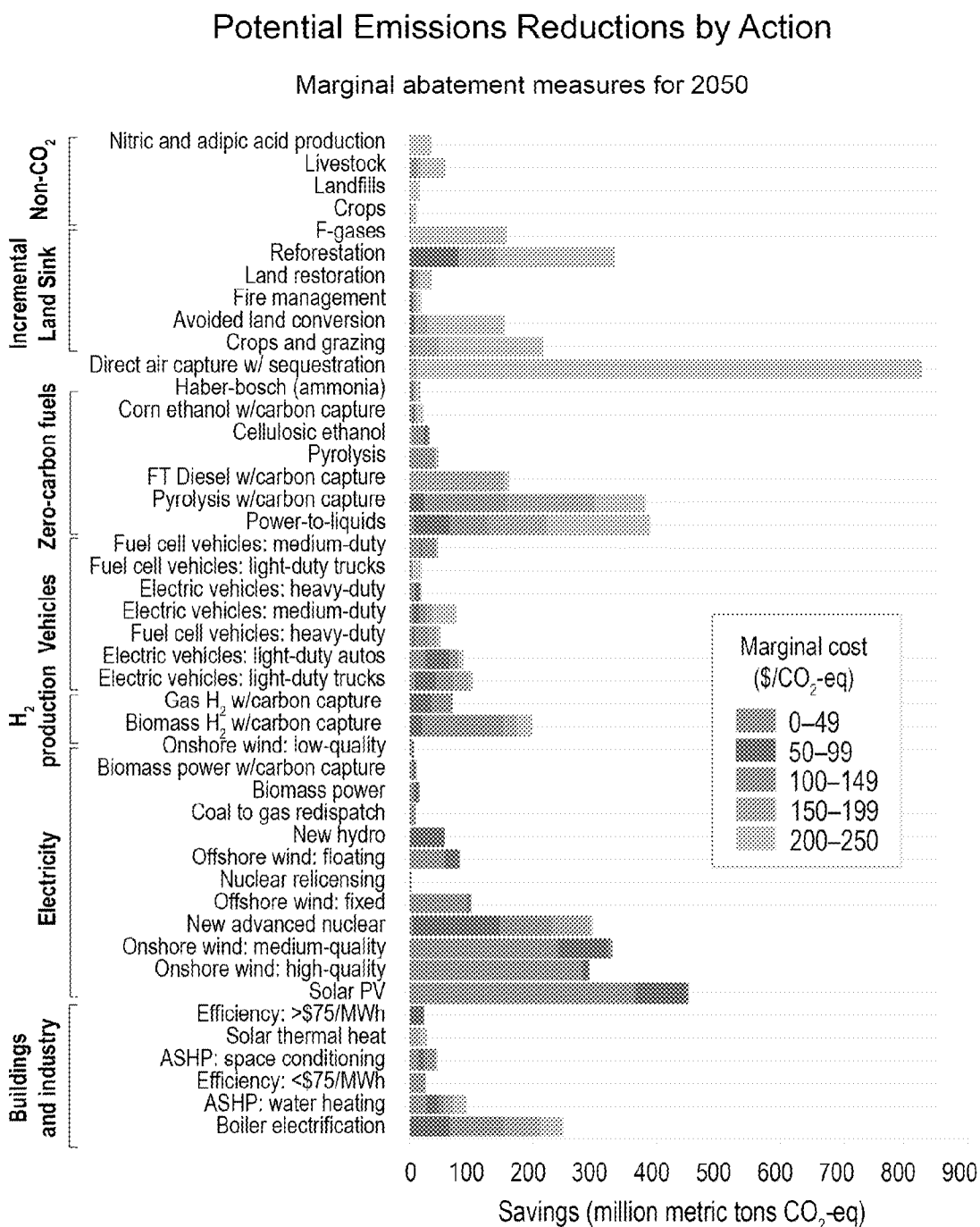
The worst consequences of climate change can still be avoided or limited by large-scale actions that rapidly decarbonize the economy and prepare communities for impacts. Many options are available to reduce emissions over the next decade that also provide immediate health and economic benefits. Longer-term planning and investment in transformative mitigation and adaptation offers the opportunity to create a healthier, more just, and more resilient Nation.

5.1. Immediate actions have near-term benefits

Aggressive action to reduce emissions is critical to slow the rate of warming and protect future generations from harm. In addition to benefitting future generations, proven mitigation efforts have other immediate benefits. Many of these options are cost effective and can help drive momentum for greater change (Figure 1.18). {Chs. 2 and 20}

- Accelerating the deployment of low-carbon technologies, promoting public transportation, providing subsidies to incentivize renewable energy and electric vehicle purchases, and improving building efficiency have significant near-term social and economic benefits. {Ch. 32.4}
- Reducing emissions of short-lived climate pollutants like methane improves air quality and saves lives while also reducing near-term warming. {14.5}
- Improvements in cropland management and practices like reduced tillage and diversification of crop rotations can increase soil carbon uptake and storage and enhance agricultural yields, strengthening the resilience and profitability of farms while also sequestering hundreds of millions of tons of CO₂ each year. {32.2}

Figure 1.18. There Are Many Cost-Effective Options in the United States for Reducing Near-Term Emissions



CAPTION: Figure 32.22 (from Ch. 32) shows potential emissions reductions and marginal costs by action. (placeholder for Overview-specific figure currently under development).

The United States has an opportunity to gain from these short-term benefits while also looking ahead. For example, cooling centers and better heat surveillance systems can save lives now—but in the long-term, people experiencing life-threatening heat for large portions of the year can't rely on cooling centers alone. Adaptation efforts can alleviate the immediate impacts of drought and floods today—but in the long-term, people living in areas with chronic water shortages or flooding will need a more permanent solution. Strategies that evaluate and plan for these long-term risks can result in even greater benefits. {Ch. 31}

5.2. Avoiding the worst impacts requires sharply reducing emissions

Limiting the worst harms from climate change requires reaching net-zero CO₂ emissions globally by 2050 and net-zero emissions of all human-caused greenhouse gases within the following few decades. Pathways to net zero involve large-scale behavioral changes and major transitions in how we power our homes, schools, and businesses; transport people and products; and interact with the land and ecosystems around us. {5.3, 6.3, 9.2, 9.3, 10.3, 13.2, 16.2, 18.3, 20.1, 24.1, 25.5, 30.5, 32.1, Focus on Blue Carbon}

In the US, reaching net-zero emissions would involve widespread implementation of a mix of proven approaches to phase out fossil fuels, reduce energy use, and drastically cut emissions from land and food systems. These include:

- Decarbonizing the electricity sector, primarily through a mix of renewable energy resources
- Transitioning to transportation and heating systems that use zero-carbon electricity sources or low-carbon fuels
- Improving energy efficiency in buildings, appliances, and vehicles and other transportation systems
- Increasing the efficiency and sustainability of food production, distribution, and consumption
- Improving land management to increase carbon storage or decrease emissions

{5.3, 32.2; Chs. 11 and 13}

Rapid growth in renewable energy generation is expected to play a central role in decarbonizing electricity systems across the United States. To reach net-zero carbon emissions by midcentury, wind and solar capacity would need to continue to increase, with projected growth rates 2 to 10 times faster each year than historical build rates. Such growth rates are supported by declining technology costs: wind and solar costs have dropped dramatically over the last decade and are expected to comprise most future capacity additions. Recent legislation is also expected to increase deployment rates of low-carbon technology. {5.3, 25.3, 32.2, 32.5}

Most net-zero scenarios also involve some amount of CO₂ removal from the atmosphere to offset any residual emissions, particularly from sectors where decarbonization is difficult. {32.3}

5.3. Transformative adaptation reduces unequal vulnerabilities

Even as planning and implementation of adaptation measures has advanced, current efforts are insufficient to avoid the worst climate harms. Adaptation actions undertaken in the US to date have generally been small in scale and incremental in approach. To adequately meet the risks of current and future climate change, more transformative adaptation is needed {Ch. 31, Introduction; 31.1}.

Table 1.3. Incremental Versus Transformative Adaptation Approaches

	Examples of incremental adaptation approaches	Examples of transformative adaptation approaches
	Using air-conditioning during heatwaves	Redesigning cities and buildings to address heat
	Reducing water consumption during droughts	Shifting water-intensive industry to match projected rainfall patterns
	Elevating homes above flood waters	Directing new housing development to less flood-prone areas

In the United States, transformative adaptation requires tackling a legacy of domestic injustices, overcoming technical and economic barriers and trade-offs, and making long-term systemic changes to institutions and norms. Effective adaptation planning involves developing and investing in new monitoring and evaluation methods to assess how actions affect different individuals and communities. However, the most successful planning reduces vulnerability by addressing the root causes of inequities—the underlying conditions that, for instance, cause extreme events to exacerbate wealth inequality or that lead to differential access to disaster assistance. {9.3, 19.1, 31.1}

Systemic change would require new and better-coordinated governance mechanisms and cooperation across all levels of government, business, and society. For example, the Santa Clara Pueblo collaborated with multiple federal agencies, tribal governments, and the state of New Mexico to restore their watershed after it was damaged by multiple fires and floods. Inclusive, participatory planning that values a wide range of perspectives and implementation of adaptation measures that leverage coordinated governance and financing have the greatest potential to improve quality of life, ensure sustainable livelihoods, protect long-term biodiversity, and drive economic productivity. {Ch. 31; 31.3}

5.4. Mitigation and adaptation actions result in systemic, cascading benefits

Actions to address climate change, from international to individual scales, can result in a multitude of benefits beyond limiting harmful climate impacts. The costs of these actions are far outweighed by benefits to both current and future generations. {13.3, 14.5, 15.2, Ch. 19, 22.2}

- Taking action to address climate change improves air quality, aids physical and mental health, increases resilience of the healthcare system, and strengthens social cohesion. {20.6, 29.2, 30.2}
- Strategic planning and investment in resilience can reduce the economic impacts of climate change, including costs to households and businesses, risks to markets and supply chains, and potential negative impacts on employment and income, while also providing opportunities for economic gain {Ch. 13; 19.2, 19.3, 26.2, 27.2; Focus on Risks to Supply Chains}
- Restoration and regeneration strategies protect ecological resources, improve water quality, strengthen biodiversity, preserve cultural traditions and heritage, and increase ecosystem resiliency. {24.4, 24.5, 26.3, 30.4; Focus on Blue Carbon}

Climate actions that incorporate inclusion and engagement with frontline communities in the design, planning, and implementation of evidence-based strategies can also reduce existing disparities and address social injustices. {24.3}

5.5. Transformative change is an opportunity for a more just Nation

The Americans most threatened by climate change are more vulnerable to harmful climate impacts because of the same racial discrimination and social injustices that lead to unequal distribution of resources and exclude marginalized communities from the benefits of historical fossil-fueled growth. Where and how fossil fuels are produced, and who bears the highest burden of pollution from oil and gas facilities, have been shaped by the country's long history of discrimination and settler colonialism. A "just transition" is the process of responding to climate change with transformative actions that address the root causes of climate vulnerability while ensuring equitable access to jobs, environmental benefits, and quality of life for all. {5.2, 15.2; Chs. 13, 16, 20, and 28}

- **Recognitional justice:** Acknowledging that certain people have borne disparate burdens related to current and historical social injustices and thus may have different needs {20.1}
- **Procedural justice:** Ensuring that the people interested in and affected by outcomes of decision-making processes are fairly and meaningfully engaged and included {20.3, 20.4}
- **Distributional justice:** Allocating resources and opportunities so that no single group or set of individuals receives disproportionate benefits or burdens {20.2, 20.5}

1 The US response to climate change has the potential to lessen climate impacts while improving
2 well-being, strengthening resilience, and prioritizing environmental justice. However,
3 transformative mitigation and adaptation measures come with challenges and trade-offs that must
4 be considered to avoid exacerbating or creating new social injustices. {Chs. 13 and 31}

5 For example, a just transformation of a city from vehicle-centric to pedestrian-focused includes
6 considering how to support people with limited mobility. As the country shifts to renewable
7 energy sources, a just transition includes job creation and training for displaced fossil fuel
8 workers. {Chs. 20, 32, and 17}

9 Equitable responses that assess such trade-offs strengthen community resilience and self-
10 determination, often fostering innovative solutions. Engaging communities in identifying
11 challenges and bringing together diverse voices to participate in decision-making allows for
12 inclusive, effective, and transparent planning processes that address the structural factors
13 contributing to inequitable climate vulnerability. {Chs. 9, 12, 13, 17, 24, and 31}

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Figure	01. Overview	1	10
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Text Region	02. Climate Trends	1	3
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Comment

This section is written as if there are no costs to emission reductions, which makes it irrelevant for ratio. It is misleading to quote reductions in costs of wind and solar without acknowledging the intermittency.

Scientific writing would include an appropriate qualifier at the start of the sentence, rather than making such a categorical declaration. For example the start of the sentence should read: "Based on standard estimates of climate sensitivity, drivers of global warming and future emission trends, achieving current national and international commitments... would require global emissions to reach net zero by around 2050." The end of the sentence is an editorial gloss that shouldn't be there. You can say that the current rate of emission decline is not sufficient to meet current national and international commitments, but you should not add the promotional line that these commitments are "designed to avoid the worst harms from climate change."

"Scientists can now rapidly quantify how much more frequent and/or severe a specific extreme event has become due to human-caused warming." This is too assertive and categorical. The event attribution literature is very new and the methods have not been subject to detailed appraisal or critique. Many of the papers are in the gray literature still. It's an inherently unfalsifiable method since it relies on model-simulated counterfactuals. Advocates for the method claim they can do these things, but readers have no way of testing the claim since the literature is backward-looking. It's very premature to say the models have been proven and the methods have been properly evaluated. It was only 2021 when elementary mathematical errors were revealed in the Allen and Tett 1999 fingerprinting method on which so much attribution work has been based.

This kind of language is so extreme it guarantees the report will be ignored. Who is your audience? Sure, activists and sympathetic journalists will eat it up and leftwing politicians will shout about it, but if your aim is just to talk to the people who are already in the climate alarmist camp there's hardly any point issuing a report. How does this sentence sound to you? "Multiple climate hazards and cascading climate impacts are disrupting essential societal systems in every part of the country." All I take away from a sentence like that is that the writing and review process for this report is one-sided and unserious.

Why do you compare a recent 30 year period to a prior 60 year period? Why not compare same-length intervals? And why describe 1901 -1960 as the first "half" of the century?

This kind of diagram and text should never have passed review up to this point. Your disaster data are not adjusted for the massive increase in the stock of buildings and equipment since the 1980s. Even if you have adjusted for price inflation, it is obviously the case that a weather event can do more damage now than 40 years ago because there are a lot more homes, buildings, and stockpiles of physical wealth in the path. If your intent is to advertise loudly that the report is biased towards alarmist advocacy, then by all means leave this section as is.

The proper comparison is not between the US and the world as a whole since every country is warming faster than the world as a whole. The proper comparison is between the US and the land average of the globe. It can't be the case that every country is warming faster than the average of all countries.

Your disaster claims are not adjusted for the massive increase in the stock of buildings and equipment since the 1980s. Even if you have adjusted for price inflation, it is obviously the case that a weather event can do more damage now than 40 years ago because there are a lot more homes, buildings, and stockpiles of physical wealth in the path. This comment also applies to p. 14

Why do you compare a recent 30 year period to a prior 60 year period? Why not compare same-length intervals? And why describe 1901 -1960 as the first "half" of the century?

The comparison to the 1980s gives the impression of cherry-picking. You have data back to the 19th century. Why pick the 1980s as the start date? You should show a chart of the number of heatwaves back to the start of the 20th century as was done in NCA4.

Here again your choice of comparison dates look like cherry-picking. In many US locations the data extend back at least to the late 1800s. Why do you only refer to the "last several decades" and in Fig 2.7 do you pick 1958? \nMcKittrick and Christy (2019) Assessing Changes in US Regional Precipitation on Multiple Time Scales Journal of Hydrology vol. 578 Nov 2019, <https://doi.org/10.1016/j.jhydrol.2019.124074> showed that trends in US precip data easily change sign as the time scale increases, and that claims about significance of trends in extreme precipitation don't hold up when using the full length of data available.

It is understandable that language around attribution reflects high confidence because the climatology literature has been stuck for decades in the optimal fingerprinting paradigm associated with Allen and Tett (1999) and Allen and Stott (2003). Repeated applications of the method keeps generating positive findings; the problem is that the propensity of the method to generate false positives has only just started to be revealed. A clue to the problem was raised in Jones et al (2016) where it was noted that the 2-variable (ANTH+NAT) signal detection regression seemed to yield significance but the 3-variable version (GHG+AERO+NAT) generally failed, even though the effects of the anthropogenic forcings were supposedly well-understood in each case. They raised, without answering, the question of whether the method is flawed. In McKittrick (2021) I have showed that the theory underlying the methods is indeed flawed. Allen and Tett (1999) introduced a biased and inconsistent estimator and misapplied the Gauss-Markov Theorem to erroneously claim it was valid. They also proposed a meaningless test that provides no information about whether fingerprinting regressions are misspecified. Note that my paper has been in print for a year and a half and Allen and Tett have declined to reply. In McKittrick (2022) I showed that the Total Least Squares algorithm of Allen and Stott (2003) also yields positively biased results when the signal detection regression is underspecified and the signals are negatively correlated. Optimal fingerprinting studies assume that the noise variances across models are all equal and all correspond to those in the observed climate, and on this basis TLS yields unbiased coefficients. But if the assumption is not true (which is likely the case) TLS is extremely unstable and biased. Taken together these papers show that the extensive application of TLS along with the Allen-Tett matrix weighted regression method (even using regularization methods rather than the Moore-Penrose pseudo inversion recommended by Allen and Tett to generate the matrix weights) yields biased and inconsistent results prone to false positives. 1/3

Meanwhile in the econometrics literature a different challenge has emerged related to the fact that temperatures and anthropogenic forcings differ by one or more orders of integration which implies they are empirically independent. Beenstock (2012), Balcombe et al. (2019) and Razzak (2022) have all shown that anthropogenic forcings exhibit $I(1)$ or $I(2)$ nonstationarity while temperatures and natural forcings are either trend stationary ($I(0)$ around a trend) or $I(0)$. This would be consistent with anthropogenic forcing dominating the temperature data only if anthropogenic forcings and temperatures are cointegrated but these authors have found this not to be the case; likewise Philips et al (2020) failed to find direct cointegration between anthropogenic forcings and temperatures. Cummins et al (2022) cast the signal detection problem into a cointegrating regression form which implies that if temperatures are $I(1)$ then signal detection regressions are potentially consistent but not if temperatures are $I(0)$. They did not test their temperature series. I have done so for a paper currently under review and found they are $I(0)$, which implies the parameter in their attribution model measuring sensitivity to greenhouse gases must be zero. You should be aware that these challenges to the confidence of attribution exist. It has taken 20 years for people outside the field of climatology to begin digging seriously into the subject. Ideally climatologists would have done so already but these analyses require specific training in advanced regression methods and it is apparently uncommon for people in the climate field to have such training. 2/3

References: \nBalcombe, Kevin, Iain Fraser and Abhijit Sharma (2019) Is radiative forcing cointegrated with temperature? A further examination using a structural time series approach." Management of Environmental Quality 30(5) DOI 10.1108/MEQ-12-2018-021. \nBeenstock, M., Y. Reingewertz and N. Paldor (2012). "Polynomial cointegration tests of anthropogenic impact on global warming." Earth System Dynamics 3:173-188 doi:10.5194/esd-3-173-2012 \nCummins, D., D.B. Stephenson and P.A. Stott. (2022). "Could detection and attribution of climate change trends be spurious regression?" Climate Dynamics March 2022 <https://doi.org/10.1007/s00382-022-06242-z> \nMcKittrick, Ross R (2022) On the choice of TLS versus OLS in climate signal detection regression. Climate Dynamics 10.1007/s00382-022-06315-z \nMcKittrick, Ross R (2021) Checking for Model Consistency in Optimal Fingerprinting: A Comment. Climate Dynamics August 2021 <https://doi.org/10.1007/s00382-021-05913-7> \nPhillips, P.C.B., T. Leirvik and T. Storelvmo (2020) "Econometric estimates of Earth's transient climate sensitivity" Journal of Econometrics 214 pp. 6—32. <https://doi.org/10.1016/j.jeconom.2019.05.002> \nRazzak, Weshah A. (2022). "The Econometrics of Global Warming," Journal of Economics and Econometrics, vol. 65(2), pages 13-47. 3/3

You can't refer to higher temperatures without also referring to the increased CO2 that drives it. The latter has a beneficial effect on US agriculture including on grasslands which support livestock production. Satellite data show substantial greening of grasslands due to rising CO2. For moderate warming the net effect of combined increase in temps and CO2 is beneficial for the crops you discuss. See Challinor, Andrew J., et al. A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change* 4.4 (2014): 287; and Dayaratna, Kevin, Ross McKittrick and Patrick J. Michaels (2020) Climate Sensitivity, Agricultural Productivity and the Social Cost of Carbon in FUND. *Environmental Economics and Policy Studies* <https://doi.org/10.1007/s10018-020-00263-w>
Barrage (2021) appears not to be in the peer-reviewed literature. The entry in the reference list is just a title.

While I don't doubt that the author group can find studies that assert all these perils, we have to ask whether, in principle, the authors believe climate cooling would convert all these losses into gains. If a warming climate is projected to injure peoples' health, ruin agriculture and cause infrastructure to collapse, would those same models predict a cooling climate would benefit crop production, promote health and extend the lifetime of infrastructure? That sure wasn't the expectation during the 1970s cooling scare. The authors need to take some account of the reward structure in academia over the past decade, in which both grants and publication counts accumulate much more easily for researchers who can find harm from warming, and there is little incentive for seriously questioning the robustness of such modeling and estimation work. Is it really the case that warming will only bring harm, costs, injuries and damages, and not a single benefit even when adaptation is taken into account? If that's what a scan of the recent literature says I think that tells us more about the academic reward structure than it does about the likely effects of climate change.

This wording is very misleading. Your data are not adjusted for increased numbers of buildings and equipment and other stuff in the path of weather events. So you haven't shown that extreme weather events are increasing, let alone that climate change is causing it. Either present properly-normalized data or leave the chart out. If you want to show a graph of weather events show that, but don't show a graph of economic damages and assume it measures climate-related weather events.

The statement "Extreme precipitation incidents are more intense and more frequent" is not true. McKittrick and Christy (2019) Assessing Changes in US Regional Precipitation on Multiple Time Scales *Journal of Hydrology* vol. 578 Nov 2019, <https://doi.org/10.1016/j.jhydrol.2019.124074> showed that trends in US precip data easily change sign as the time scale increases, and that claims about significance of trends in extreme precipitation don't hold up when using the full length of data available.

Same comment as above. The assertion that climate change has caused changes in US precipitation and incidence of extremes is contradicted by published evidence.

onal decision-makers. It sounds like an extreme environmentalist pamphlet, not a serious scientific
/ issue. Costs of capacity installation are largely irrelevant for system planning if the power source

ific report. It makes sweeping generalizations that go beyond the available literature. Economic
ce is unreliable. When Germany faced the sudden shutdown of the Nordstream pipeline they di

research does not imply that every increment of warming everywhere is harmful, instead it shc
dn't start putting up windmills and solar panels, they fired up coal plants and built an LNG impor

ows that there are many regions that potentially benefit from small warming increments. Nor are
t terminal in 8 months. Because they need cost-effective and reliable power. Who is the intended

e all emission reduction activities beneficial: the vast majority fail any reasonable cost-benefit test. What is the intended audience of this report? Anyone in a position of authority over energy system planning will not

est, which is why they haven't been implemented despite decades of advocacy. This section pre
ot be impressed by your glib claims about the falling costs of renewables, instead it will serve sa

supposes that climate change is "fuelling" increases in extreme weather yet the IPCC AR6 fails to
s yet another signal that this report is advocacy for the green cause, not objective and reliable in

o report such a connection for most types of extreme weather. As an opening summary that will
information to aid decision-making.

ll attract much attention this section needs to set a tone of balance, not sound like an activist sc

reed--that is unless you want the entire report to be dismi

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November 7, 2022

1	Chapter Contents	
2	Introduction	3
3	Key Message 3.1. Drivers of Climate Change	3
4	Key Message 3.2. Climate Sensitivity and Climate Feedback	7
5	Key Message 3.3. Changes at Regional Scales	10
6	Key Message 3.4. New Scenarios and Climate Projections.....	14
7	Key Message 3.5. Large Ensemble Simulations	16
8	Key Message 3.6. Extreme Event Attribution.....	17
9	Key Message 3.7. Observations for Improving Process Understanding and Modeling.....	18
10	Key Message 3.8. Water Cycle Changes.....	19
11	Key Message 3.9. Changes in the Carbon and Biogeochemical Cycles	22
12	Key Message 3.10. Changes in Ocean and Cryosphere and Sea Level Rise	24
13	Key Message 3.11. Atmospheric Circulation Changes.....	28
14	Key Message 3.12. Changes in Extreme Events	29
15	Traceable Accounts	33
16	References.....	51
17		
18		

1 Introduction

2 The Earth system consists of the atmosphere, land, oceans, and cryosphere, which interact and
3 cycle energy, water, and essential elements of life such as carbon, nitrogen, and phosphorus.
4 Powered by the sun, these interactions and cycles determine Earth's climate, which naturally
5 varies at a broad range of timescales from days to millennia through diverse Earth system
6 processes.

7 Since industrialization, human activities have dramatically altered atmospheric composition and
8 land cover, with consequential impacts on climate. Human-caused emissions of greenhouse
9 gases have warmed the planet by trapping more outgoing energy, leading to a change in the net
10 energy balance at the top of the atmosphere. The net increase in energy input warms the air and
11 the surface and increases moisture in the lower atmosphere, resulting in significant changes in
12 Earth system processes, including changes in circulations, clouds, and precipitation and melting
13 of sea ice, glaciers, and ice caps. The increase in energy input also provides fuel for increasing
14 the frequency and intensity of extreme weather events such as heatwaves and convective storms.

15 In recent years, advances have been made in understanding, attributing, and projecting climate
16 change. These advances are facilitated by new and diverse observations, improved models and
17 experiments, and combining observations and models to support multiple lines of evidence and
18 inquiry. This chapter introduces the drivers of climate change and the climate response to those
19 drivers and highlights recent advances in observations, modeling, and understanding of Earth
20 system processes that underpin the many facets of regional climate change.

21 Key Message 3.1. Drivers of Climate Change

22 Human activities—primarily emissions of greenhouse gases—have caused nearly all global
23 warming observed over the industrial era (*very high confidence*). Changes in natural
24 climate drivers had globally small and regionally variable long-term effects over that
25 period (*high confidence*).

26 Shifts in climate at the global scale occur primarily in response to processes that change the
27 balance between incoming and outgoing energy at the top of the atmosphere (TOA). The drivers
28 of change are both natural and human-caused and may be transient or long-lived. Changes in
29 TOA net radiation balance resulting from a perturbation in climate drivers can be quantified in
30 terms of the effective radiative forcing (ERF), measured in units of Watts per square meter (W m^{-2}).
31 The main natural drivers of climate change—variations in solar radiation and volcanic
32 aerosols—have negligible contributions to long-term climate forcing (Boucher et al. 2013;
33 Forster et al. 2021). Warming from fossil fuel emissions of carbon dioxide is expected to last
34 centuries to millennia, because of the slow rate of the natural removal processes. Changes in
35 climate may be further amplified or diminished through feedbacks in the climate system.
36 Feedbacks are processes changed by the warming which then modify the TOA radiation balance
37 and the overall level of warming. In the surface–albedo feedback, for example, warming melts

ice cover over the land and ocean, exposing darker surfaces beneath that absorb more energy rather than reflecting it, contributing to further warming. See Chapter 2 of the Climate Science Special Report (CSSR; Fahey et al. 2017) for further details on emissions sources, radiative forcing, and ERF.

Anthropogenic Drivers

Well-Mixed Greenhouse Gases

Since the Fourth National Climate Assessment (NCA4), global atmospheric abundances of the main well-mixed greenhouse gases (WMGHGs) including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), have continued to increase (see Ch. 2). Atmospheric abundances of halogenated gases have also changed, some increasing and some decreasing due to ozone depletion policies. Preindustrial to present day (1750–2019) increases in WMGHGs contributed the bulk of the total human-caused forcing, with increases in CO₂ contributing an ERF of $2.16 \pm 0.26 \text{ Wm}^{-2}$, followed by $0.54 \pm 0.11 \text{ Wm}^{-2}$ from CH₄, $0.41 \pm 0.08 \text{ Wm}^{-2}$ from halogenated compounds, and $0.21 \pm 0.03 \text{ Wm}^{-2}$ from N₂O (Forster et al. 2021).

The growth in global atmospheric CO₂ levels since 1750 was primarily driven by direct emissions from human activities such as fossil fuel combustion, cement manufacturing, and land-use change. About $41\% \pm 11\%$ of the $700 \pm 75 \text{ PgC}$ of CO₂ emissions between 1750 and 2019 remain in the atmosphere today, with the rest removed by oceans and the land biosphere (Canadell et al. 2021).

Methane is considered both a WMGHG and a short-lived climate forcer due to its chemical reactivity and an approximate 10-year atmospheric lifetime. Methane is produced by both natural processes and human activities. Observational evidence points to microbial sources (agriculture, waste, and wetlands) as the predominant cause of the increase in global growth in atmospheric CH₄ since 2006 (Schaefer et al. 2016; Lan et al. 2021).

In addition to its direct effect on radiative forcing, CH₄ also has an indirect influence through its chemical effects on other climate drivers including CO₂, ozone, stratospheric water vapor, aerosols, and halogenated gases. This leads to an increased effect of CH₄ on the amount of energy trapped in the Earth system. Over 100 years, a given mass of CH₄ emissions is about 30 times more efficient at trapping energy in the climate system than the same emitted mass of CO₂ (Forster et al. 2021).

The increase in atmospheric N₂O levels since 1750 is small compared to that of CO₂ and CH₄, though rates have increased in recent years due to increased nitrogen fertilizer use in agriculture (Tian et al. 2020). N₂O has an atmospheric lifetime of about 116 years and is nearly 300 times more efficient at trapping energy than CO₂ (Forster et al. 2007).

WMGHGs also include many manufactured gases with atmospheric lifetimes greater than several decades, such as sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), and perfluorocarbons (PFCs). The atmospheric abundances of most

CFCs have continued to decline in response to regulations under the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments (Gulev et al. 2021). Atmospheric levels of HFCs are increasing while the rates of atmospheric growth of major HCFCs have slowed down in recent years.

Non-Methane Short-Lived Climate Forcers

Short-lived climate forcers (SLCFs) are chemically reactive in the troposphere (lower atmosphere), with atmospheric lifetimes typically shorter than two decades, and include ozone, aerosols, and methane. Most SLCFs are also air pollutants or precursors for air pollution (see KM 14.5). An assessment of the ERF effects for two primary non-CH₄ SLCFs are given below.

Ozone: Ozone is a greenhouse gas that occurs naturally throughout the atmosphere and is a harmful air pollutant near the surface (KM 14.1). Ozone is produced in the troposphere by chemistry driven by sunlight and emissions of methane, nitrous oxides, carbon monoxide, and non-methane volatile organic compounds. Increases in human-caused emissions of these precursors since preindustrial times are responsible for increases in tropospheric ozone (Myhre et al. 2013; Szopa et al. 2021). In the stratosphere, increases in human-caused halogenated ozone depleting substances (ODSs) have contributed to declining ozone abundances. Over the period 2000–2017, stratospheric ozone concentrations have increased slightly in response to declining ODSs because of the Montreal Protocol and its amendments (Gulev et al. 2021). The combined changes in tropospheric and stratospheric ozone from the preindustrial era to the present have had an overall warming effect of $0.47 \pm 0.23 \text{ Wm}^{-2}$, with a smaller contribution from stratospheric ozone changes (Forster et al. 2021).

Aerosols: Aerosols are emitted directly from human activities and natural processes and are also formed in the atmosphere via reactions involving gaseous precursor emissions. Ice core records indicate that aerosols increased from the preindustrial era until the 1970s and 80s, driven by northern mid-latitude emissions, and declined thereafter (Gulev et al. 2021). This decline is attributed to reductions in emissions from Europe and North America due to air quality regulations. Satellite data and ground-based records over the modern period confirm the decline in aerosols over the northern mid-latitudes and southern hemisphere continents but show increases over South Asia and East Africa (Gulev et al. 2021; Quaas et al. 2022). Globally, aerosol concentrations have been declining since 2000. Aerosols from human activities are also air pollutants (KM 14.1) and influence Earth's radiation balance directly by scattering or absorbing solar radiation, through interactions between aerosols and clouds, and by changing the surface reflectivity when light-absorbing aerosols are deposited on snow and ice. Changes in aerosols over the period 1750–2014 have had an overall cooling effect of $-1.3 \pm 0.7 \text{ Wm}^{-2}$ (Foster et al. 2021).

Land Use Effects on Surface Albedo

Anthropogenic water storage and use modifies the land surface and alters the surface energy balance. Increased water storage on land reduces surface reflectivity and has a localized cooling effect due to evaporation. Irrigation of crops has a similar localized cooling effect through both evaporation and plant transpiration (Chen and Dirmeyer 2019). Changes in land use have contributed a net negative ERF (cooling effect) of $-0.20 \pm 0.10 \text{ W m}^{-2}$ (Forster et al. 2021).

Natural Drivers

Solar Irradiance

Climate forcing from changes in solar irradiance are small relative to changes in anthropogenic greenhouse gases over the industrial era. Changes in solar irradiance over the period 1750–2019 have contributed an ERF of $0.01 \pm 0.07 \text{ W m}^{-2}$, (Forster et al. 2021).

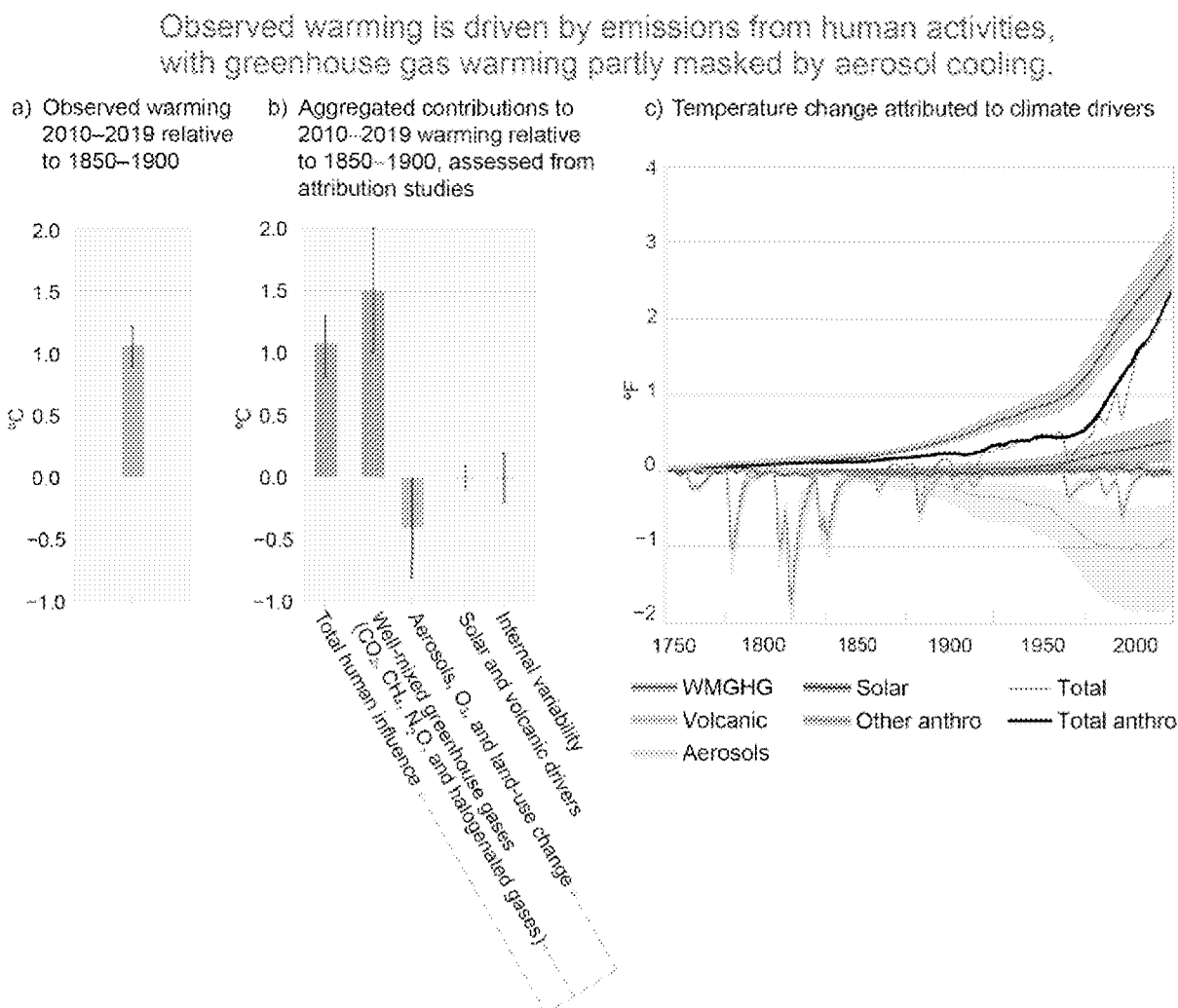
Volcanic Aerosols

Sulfate aerosols formed in the stratosphere from injections of sulfur dioxide (SO_2) from explosive, episodic volcanic eruptions and more frequent smaller eruptions reduce incoming solar radiation and lead to a cooling effect. Volcanic aerosols can also trigger changes in upper tropospheric clouds, leading to warming (Friberg et al. 2015; Schmidt et al. 2018), although the magnitude of this effect is highly uncertain (Zhu and Penner 2020). Quantitative assessment of the net ERF over the industrial era for volcanic aerosols shows negligible effects on the long-term temperature trends.

Global Surface Temperature Response to Climate Drivers

A notable recent advance is the quantification of the global surface air temperature change over the preindustrial to present day due to forcings from changes in different climate drivers (Forster et al. 2021). Figures 3.1a and 3.1b show that observed warming in 2010–2019 (compared to 1850–1900) is dominated by contributions from WMGHGs and ozone. This warming has been partially counteracted by the cooling effect from aerosols and land-use change. Because of declining aerosols, the global aerosol cooling effect has weakened since about 1980, and the rate of global warming has increased, mainly due to increasing greenhouse gases (Figure 3.1c). The aerosol cooling effect has a strong regional dependence (Szopa et al. 2021), contributing to differences in regional climate change (KM 3.3). Natural drivers over the historical period have contributed a small, highly variable cooling effect.

1 Figure 3.1. Global Surface Temperature Response



2
3 CAPTION: (a) Observed global warming in 2010–2019 compared to 1850–1900, (b) temperature change
4 over the same period attributed to different climate drivers and natural climate variability based on
5 climate models and observations, and (c) evolution of global warming attributed to different drivers
6 from 1750 to 2019. Whiskers in (a) and (b) show the very likely range while shaded uncertainty bands in
7 (c) show very likely (5%–95%) ranges. Adapted from IPCC 2021 and Forster et al. 2021.

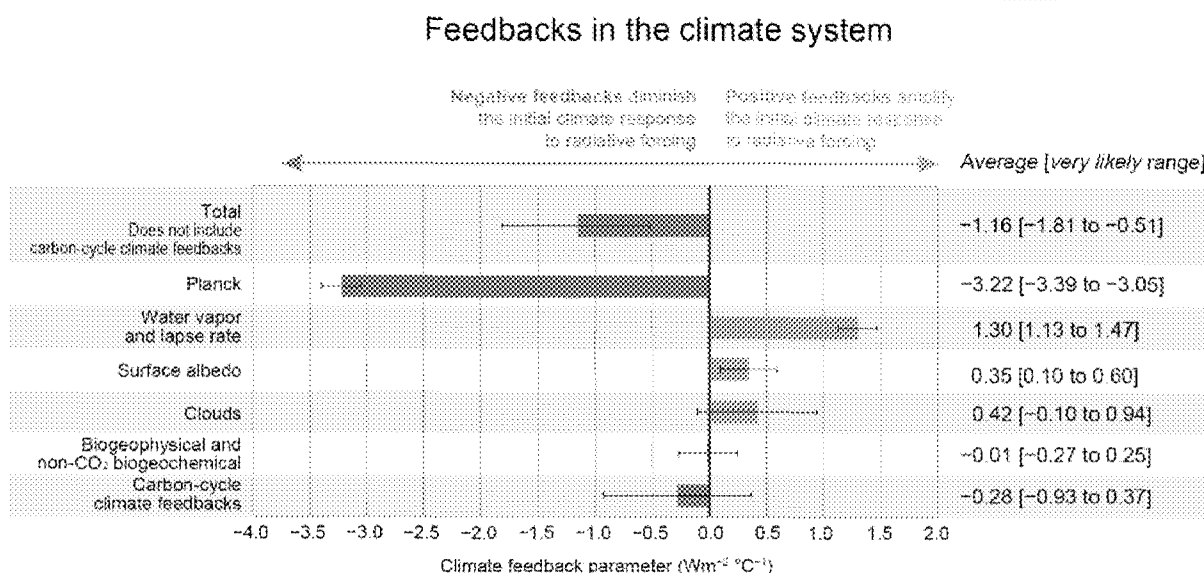
8 Key Message 3.2. Climate Sensitivity and Climate Feedback

9 Recent improvements in the understanding of how climate feedbacks vary across timescales
10 have narrowed the estimated *likely* range of warming expected from a doubling of
11 atmospheric carbon dioxide by 50% to between 4.5°F and 7.2°F (*high confidence*).

12 The total climate response for a given forcing is an important indicator of the expected climate
13 change impacts. This response is commonly characterized by the equilibrium climate sensitivity

(ECS), defined as the change in global average surface temperature after the climate system reaches a steady state following a doubling of the atmospheric CO₂ concentration. A larger value of ECS indicates larger increases in global warming for a given increase in greenhouse gases. ECS depends both on the ERF from a doubling of CO₂ and the sum of climate feedbacks that can either amplify (a positive feedback) or dampen (a negative feedback) the temperature change. The primary feedbacks arise from increased emission of longwave radiation that cools the warmer planet (Planck feedback), increases in atmospheric water vapor (a greenhouse gas), changes in the vertical profile of atmospheric temperature, reductions in the surface area covered by reflective snow and ice, and changes in cloudiness. Cloud feedbacks are the largest source of ECS uncertainty (Figure 3.2; Sherwood et al. 2020; Forster et al. 2021). The response of the carbon cycle to climate warming contributes additional uncertainty (KM 3.9).

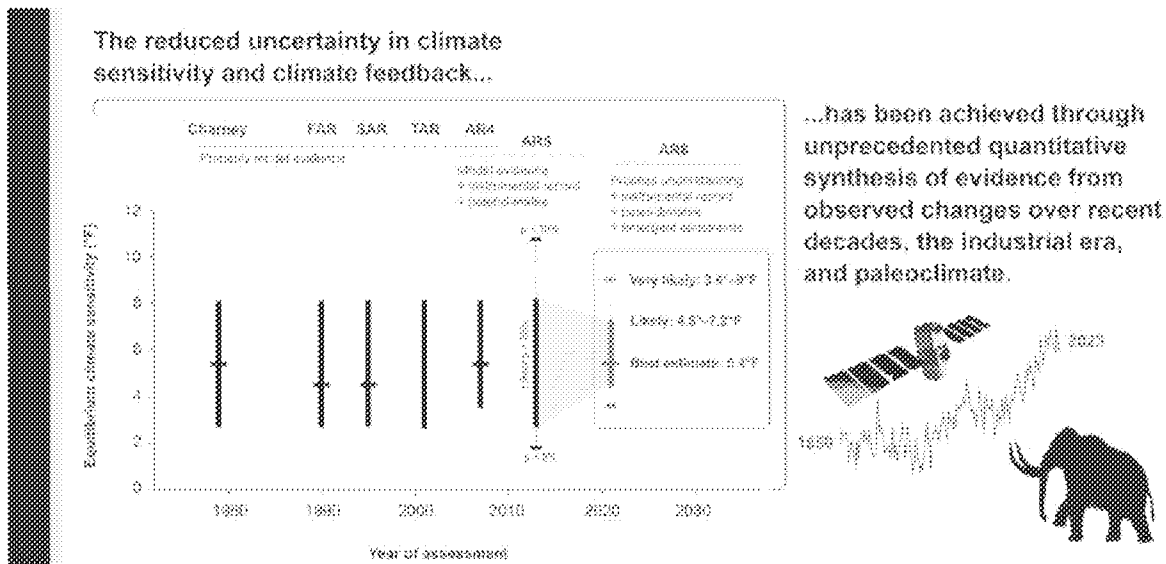
Figure 3.2. Feedbacks in the Climate System



CAPTION: Assessed values of feedbacks acting in the climate system. The total feedback is the feedback that contributes to the assessed value of climate sensitivity. Bars denote the average feedback values and uncertainties represent *very likely* ranges. Adapted from Figure TS.17 of Arias 2021.

The key development since NCA4 is that the ECS uncertainty range has narrowed (Sherwood et al. 2020; Forster et al. 2021). Recent assessments place ECS between 4.5°F and 7.2°F (2.5°C and 4.0°C), a 50% uncertainty reduction from previous assessments (Figure 3.3). It is *virtually certain* that ECS is greater than 2.7°F (1.5°C), guaranteeing significant climate change impacts from ongoing increases in CO₂ and other greenhouse gases.

Figure 3.3. Advances in Understanding Climate Sensitivity and Climate Feedback



CAPTION: The recently reduced estimated range of equilibrium climate sensitivity (left) reflects advances in understanding of how climate feedbacks operate across timescales and an improved ability to combine physical constraints with observational data from recent decades, the industrial era, and paleoclimate records (right). Adapted from Figure TS.16a of Arias 2021.

This uncertainty reduction results from advances in combining observations and targeted modeling results from nearly independent lines of evidence, each of which generally agrees on the values of ECS. The lines of evidence include (a) observed present-day variations from which cloud and other climate feedbacks are inferred; (b) observed temperature changes between the preindustrial period and present and associated relationships to ERF; and (c) estimated temperature and radiative forcing changes for multiple warm and cold periods in paleoclimate records (Sherwood et al. 2020).

Advances since NCA4 include

- Increased use of present-day observations to determine cloud and other climate feedbacks. Confidence in inferring feedbacks for centennial-scale climate changes from present-day variations is bolstered by “emergent constraints” found in Coupled Model Intercomparison Project (CMIP) model ensembles (see Appendix 3).
- Increased use of very-high-resolution cloud-resolving models to determine expected changes in response to the warmer conditions.
- Greater understanding of how changes in the spatial distribution of sea surface temperature over the historical period affected climate feedbacks.

- Greater availability of reconstructed temperatures and ERF values for paleoclimate and greater confidence in how to account for the state-dependence of climate feedbacks and departures from equilibrium.

The reduction of uncertainty in ECS was accompanied by reduced uncertainty in the cloud feedback. There is greater confidence that the sum of feedbacks over all cloud types is positive (i.e., a warming effect) and primarily results from increases in the altitude of high-level clouds and decreases in the amount of marine stratocumulus and continental low-level clouds. A previously identified negative feedback arising from the transition of cloud phase from ice to liquid as the planet warms (Mitchell et al. 1989) is now thought to be substantially smaller based on new observational evidence (Ceppi et al. 2016; Terai et al. 2016).

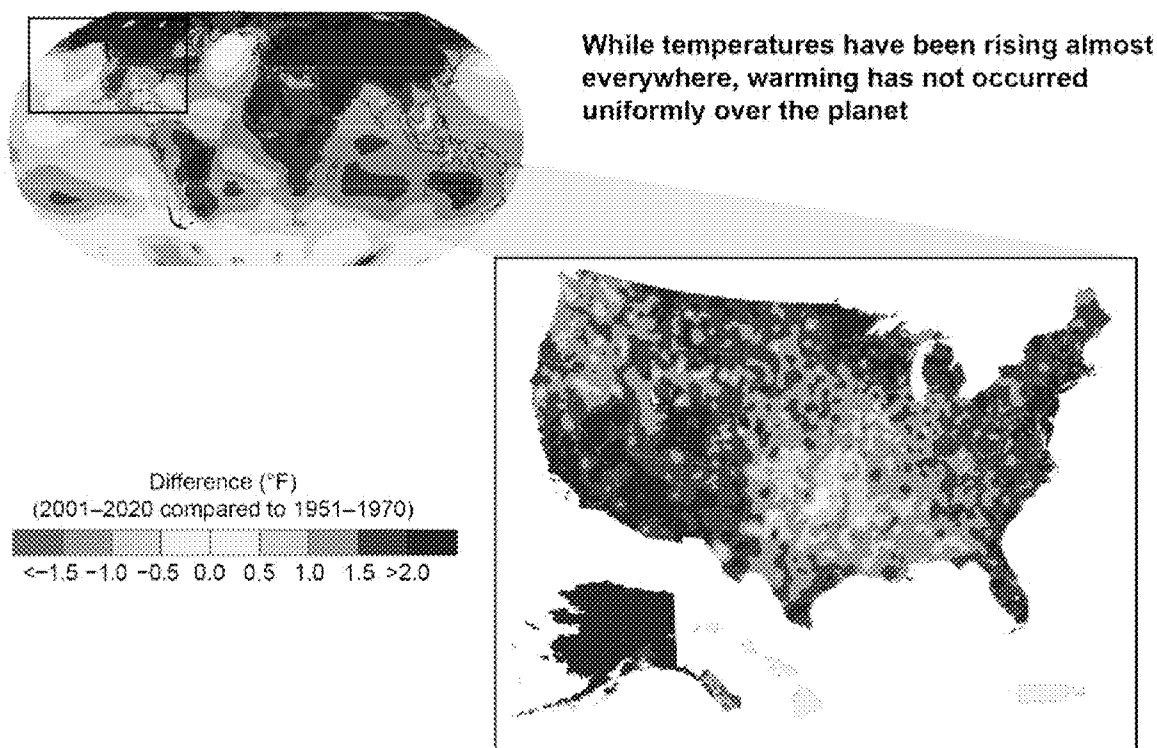
The new assessed range of ECS relies on observational analyses and selected modeling evidence but does not consider the ECS values from climate models directly. Models with ECS values outside of the assessed range are thought to have *unlikely* values of ECS. In particular, the CMIP6 models with ECS values greater than 9°F (5°C) may simulate an unrealistically early timing of reaching a given global warming level (GWL). Despite their unrealistic timings, these models may still be used to estimate the climate impacts occurring at a given GWL (Hausfather et al. 2022).

Key Message 3.3. Changes at Regional Scales

Changes in regional climate can differ substantially from changes in global-scale averages, and natural variability in the climate system limits the precision of regional-scale projections. Thus, it is important to account for regional differences as well as natural variability when providing climate change information. (*Very High Confidence*)

At the continental scale (less than 10,000 km), the climate response to anthropogenic forcing is affected by differences in how quickly land and ocean areas warm, with land generally warming more than the ocean. This is because land areas have a lower heat capacity, and thus respond more quickly than the ocean to anthropogenic forcing, and because of the larger cooling effect of evaporation from the ocean surface. Therefore, North America generally warms more than adjacent oceans (Figure 3.4). Precipitation responses tend to be organized in latitude bands such as the tropics, subtropics, midlatitudes, and high latitudes. Both temperature and precipitation responses can be shaped by anthropogenic changes in the atmospheric circulation (KM 3.11).

1 **Figure 3.4. Regional Differences in Climate Response**



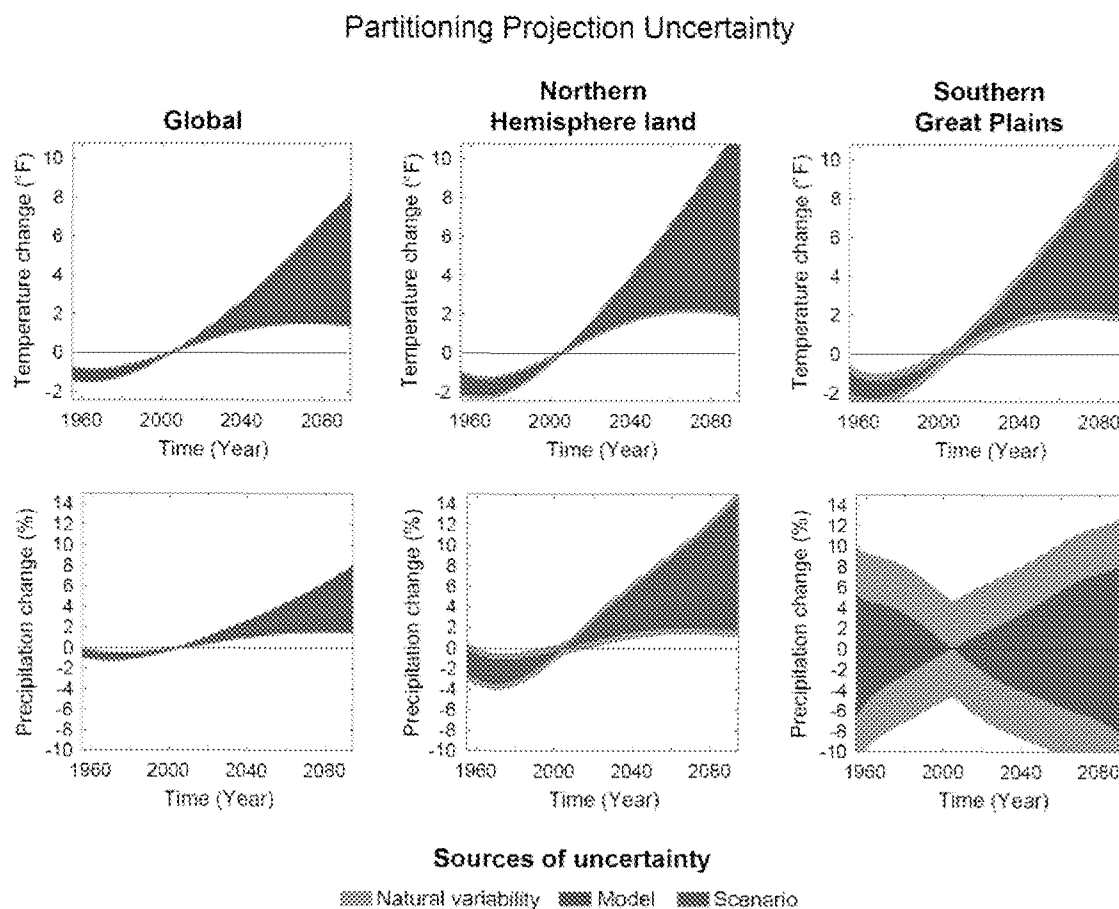
2
3 CAPTION: While temperatures have been increasing almost everywhere, warming has not occurred
4 uniformly over the planet. Temperatures over land have been increasing faster than over the ocean, and
5 the Arctic has been warming at more than twice the global average rate. Sources: University of
6 California, Los Angeles; University of California, Davis; NOAA NCEI; and CISESS NC.

7 At the regional scale (less than 1,000 km), variations in land surface properties are associated
8 with differences in the local climate responses to anthropogenic forcing. Examples (Figure 3.4,
9 US panel) include greater warming at snow margins in western US mountains (Walton et al.
10 2017), greater warming in inland areas separated from the coast by California mountain ranges
11 (Sun et al. 2016), greater warming in extremely arid landscapes (Zhou et al. 2016), shifts of
12 precipitation downwind in mountainous areas (Siler and Roe 2014), snowfall loss at higher
13 elevations where temperatures increase above the freezing line (Ohba et al. 2020; López-Moreno
14 et al. 2011), changes in snowmelt-driven runoff as a function of elevation (Huang et al. 2020),
15 changes in snowfall over large lakes (Gula and Peltier 2012) and changes in evaporation and soil
16 moisture due to variations in vegetation. Regional variations in the changes of temperature and
17 precipitation are also driven partly by the regional distributions of aerosols, which interact with
18 clouds and radiation (Liu et al. 2018). Downscaling is often used to simulate these phenomena
19 and to convert global model output from lower (100 km) to higher resolution (1–10 km) for
20 adaptation planning (see Appendix 3).

1 Natural Variability and Uncertainty

2 At all spatial scales, the climate response is forced by anthropogenic drivers, which are *external*
3 to the climate system. This response occurs against a background of *natural* climate variability.
4 Such variability is generated by natural processes, for example by atmosphere–ocean interaction
5 (e.g., El Niño and La Niña events), atmosphere–land interaction, or chaotic variability within the
6 atmosphere itself. Depending on the sequencing and magnitude of natural variability and the
7 magnitude of the climate change response, natural variability can either mask the climate change
8 signal, amplify it, or be overwhelmed by it. Natural variability therefore adds uncertainty to
9 climate change projections. Because the sequencing of natural variability is unpredictable on
10 timescales longer than a decade, this component of uncertainty in climate change projections is
11 irreducible. This is in contrast with the uncertainty associated with the climate change response,
12 which arises from lack of information about future greenhouse gas and aerosol emissions, as well
13 as incomplete understanding of climate processes—knowledge gaps that can, in principle, be
14 filled (KM 3.2). The magnitude of natural variability generally increases as spatial scales
15 decrease. At the scale of a typical Earth system model (ESM) grid, natural variability is the
16 dominant source of uncertainty in precipitation and temperature projections over much of the
17 United States (Figure 3.5). On continental scales, model and scenario uncertainty become more
18 important (Lehner et al. 2020). Therefore, at the regional scales and the multidecadal time
19 horizons relevant for adaptation planning, uncertainty due to natural variability can be a larger
20 contributor to overall uncertainty in climate change than model or scenario uncertainties (e.g.,
21 Dong et al. 2021a and Figure 3.5).

1 **Figure 3.5. Natural Variability and Climate Model and Scenario Uncertainties**



2

3 CAPTION: The relative importance of different sources of uncertainty (natural variability, model

4 uncertainty, and scenario uncertainty) for projections of decadal mean temperature and precipitation

5 for the globe, Northern Hemisphere land, and the Southern Great Plains. The shadings are constructed

6 as a symmetric 90% range around the multi-model multi-scenario mean projection following the

7 methodology from Hawkins and Sutton (2009) and updated with 29 CMIP6 models and 4 scenarios

8 following Lehner et al. (2020). Sources: Cornell University, National Center for Atmospheric Research,

9 and Pacific Northwest National Laboratory.

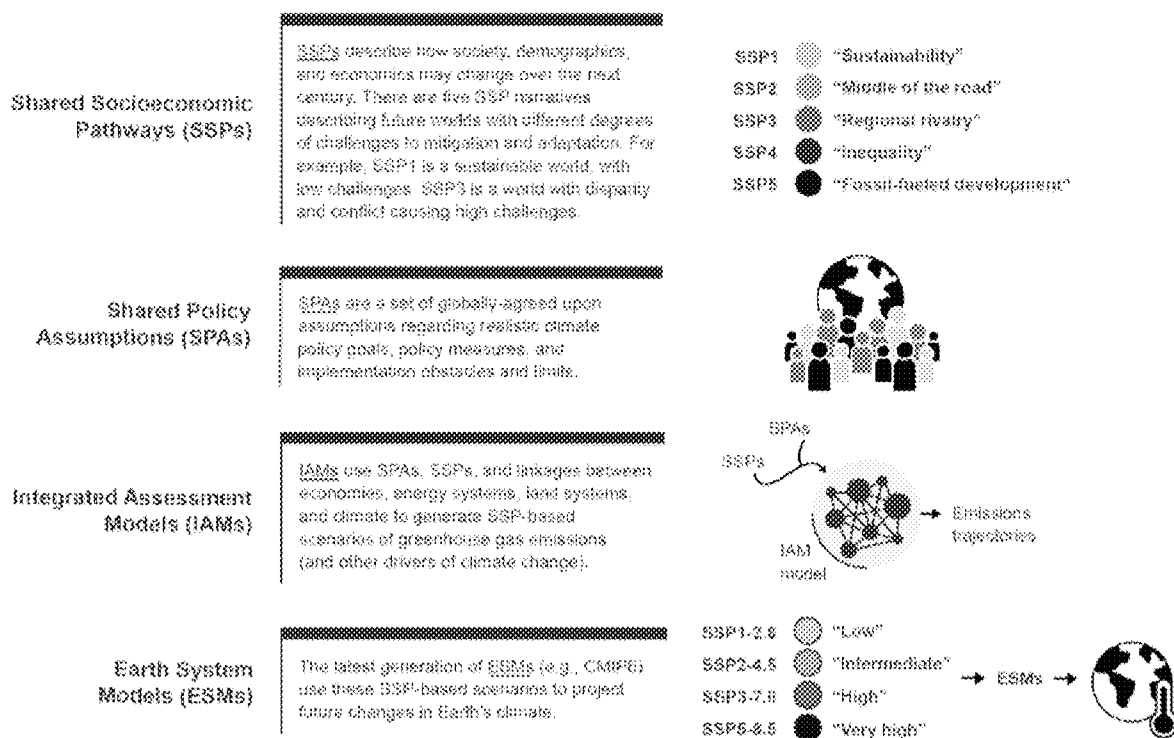
1 Key Message 3.4. New Scenarios and Climate Projections

2 A new generation of Earth system models has produced an updated set of projections under a
3 number of newly developed policy-relevant scenarios. A number of Earth system models
4 have been run at significantly higher resolution (about 20–50 km) than the previous
5 standard (about 100–200 km) for focused experiments to explore particular aspects of
6 climatic changes, like tropical cyclones, that cannot be simulated by coarser-resolution
7 models.

8 ScenarioMIP (O'Neill et al. 2016) organized the main set of 21st century projection experiments
9 under the latest phase of the Coupled Model Intercomparison Project, CMIP6. These CMIP6
10 projections used newly developed scenarios based on Shared Socioeconomic Pathways (SSPs,
11 Figure 3.6; O'Neill et al. 2014; Van Vuuren et al. 2014; Riahi et al. 2017). Five SSPs represent
12 alternative plausible trajectories of 21st century gross domestic product and population growth
13 and the pace and pervasiveness of socioeconomic and technological progress within individual
14 nations and across the world. SSP-specific drivers are used in integrated assessment models
15 (IAMs) to simulate the corresponding evolution of the energy system, and the resulting
16 greenhouse gas (GHG) trajectories. These are in turn used by ESMs to drive their 21st century
17 projections. Some of these trajectories are also modified by imposing mitigation policies that
18 meet specific warming targets (e.g., 1.5°C or 2°C above preindustrial levels) by the end of the
19 century (Kriegler et al. 2014). Figure 3.6 describes this process step by step.

20 Note that the mitigation assumptions in the various scenarios are not directly relatable to the
21 mitigation discussion in Chapter 32, where the analysis is specifically centered on the current
22 mitigation targets of the US in view of the Paris goals. The stringent goals of net-zero CO₂
23 emissions by 2050 that the Mitigation chapter discusses for the United States are, however,
24 consistent with the lowest scenario adopted in ScenarioMIP.

1 Figure 3.6. SSP-Based Scenarios and their Use in Climate Model Projections



CAPTION: The chain of development leading to Earth system model experiments under CMIP6 ScenarioMIP, the most up-to-date 21st century climate change projections. Five societal development pathways (the SSPs) were produced. Then, assumptions about climate mitigation policies that could be consistently applied to those socioeconomic futures were developed (the SPAs). Integrated assessment models took these baseline or mitigated pathways and produced alternative plausible trajectories of greenhouse gas emissions and land-use change. Earth system models used those forcings as inputs to produce the new CMIP6 scenarios of climate outcomes. Sources: Cornell University, National Center for Atmospheric Research, and Pacific Northwest National Laboratory.

The new scenarios are labeled "SSPX-Y" where SSPX (with X ranging from 1 to 5) identifies the SSP used to produce the GHG trajectories. Y indicates the magnitude of the radiative forcing by 2100. The main 21st century trajectories from the CMIP6 ensemble are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, along with SSP1-1.9, the lowest emission trajectory, which is designed to stay below 1.5°C of warming above preindustrial levels. These scenarios are intended to provide a representative set of plausible alternative pathways of GHG and aerosol emissions and land-use changes, according to alternative societal and economic development trends over the 21st century. Three new scenarios correspond to three of the Representative Concentration Pathway (RCP) scenarios used in CMIP5 (SSP1-2.6 with RCP2.6, SSP2-4.5 with RCP4.5, and SSP5-8.5 with RCP8.5) in their overall forcing levels albeit with different details in their composition of gases and land use. Scenario projections can be used to explore climate outcomes

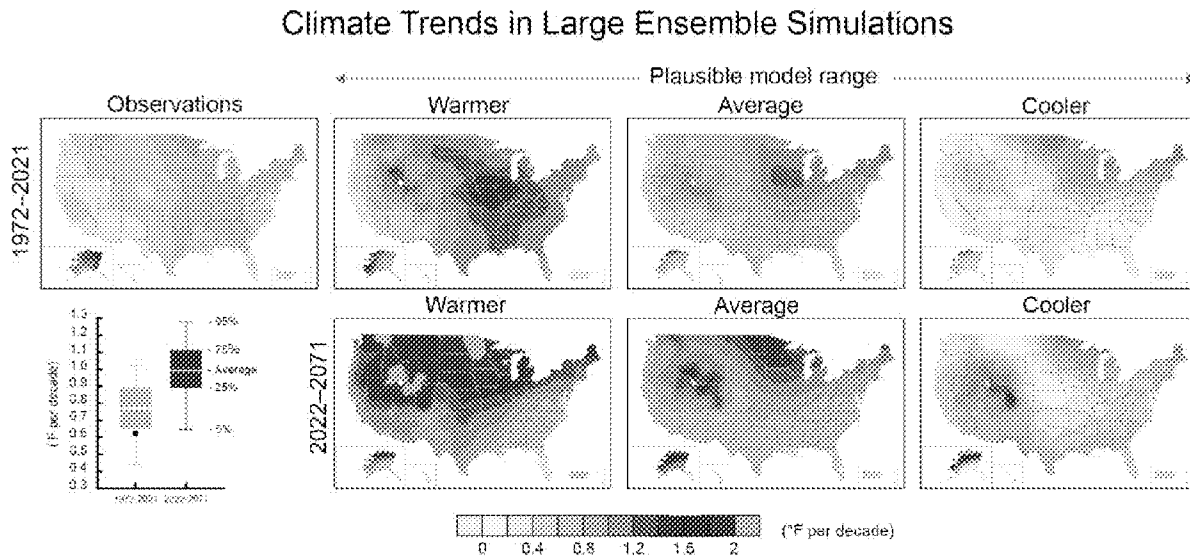
under a coherent future trajectory of GHGs and other anthropogenic forcings. An alternative perspective on the effects of climate change uses GWLs as an organizing principle. One can ask when a certain GWL will be reached for a given scenario and climate model, thus connecting the two perspectives. CMIP6 includes many experiments performed by many ESMs at about 100 km resolution (Eyring et al. 2016). A multi-model approach, the High Resolution Model Intercomparison Project (HighResMIP) (Haarsma et al. 2016), is featured for the first time in CMIP6 to systematically investigate the impact of horizontal resolution. Models participating in HighResMIP have resolutions between 20 and 50 km and show more realistic simulations of intense storms and resulting precipitation (Wehner et al. 2021; Gao et al. 2020). At these resolutions they can explicitly represent tropical cyclones, and their simulations (Wehner et al. 2018; Roberts et al. 2020a, 2020b) support the conclusion of a global decrease in tropical cyclone frequency (Knutson et al. 2020) together with an increase in intensity with warming. Their more refined topography also enhances their representation of local processes, such as the effects of warming on mountain snowpack—an important water source for the western United States (Siirila-Woodburn et al. 2021).

Key Message 3.5. Large Ensemble Simulations

New experiments from multiple climate models that capture both natural variability uncertainty and model uncertainty have improved our ability to understand and quantify expected climatic changes and the relative contributions of human-caused climate change and natural climate variability at regional scales (*high confidence*).

In climate modeling, one must choose a starting point called the initial condition for each experiment. This starting point may be altered by a small random perturbation, the so-called butterfly effect, which can subsequently alter the sequence of weather and climate events and hence, the future course of the natural variability simulated by the model. Recently climate model experiments have been conducted using multiple climate models with small random perturbations at the start of the simulations. This has resulted in a large ensemble of simulations called an initial-condition large ensemble. The advent of these initial-condition large ensembles (henceforth referred to as large ensembles) in climate modeling provides a direct framework for quantifying the relative contributions of external drivers and natural variability to regional climate change by sampling different possible sequences of natural variability superimposed upon a common forced response (Deser et al. 2020). The application of large ensembles to assess the possible range of climate trends at local and regional scales is a major advance in recent years (Figure 3.7). A new insight from the large ensemble archive is that different models have different representations of natural climate variability and how such variability responds to anthropogenic climate change.

1 Figure 3.7. Climate Trends in Large Ensemble Simulations



CAPTION: Past and projected future trends in winter (December–February average) air temperature (°F per decade). (Top row) Observed trends (left panel) and the plausible (5th-to-95th percentile) range of modeled trends (remaining panels) from the CESM2 100-member Large Ensemble over the past 50 years (1972–2021). (Bottom row) As in the top row, but for model projections over the period 2023–2072 under the SSP3-7.0 radiative forcing scenario. Left panel shows the distribution of US-average trends from CESM2; the observed trend value is indicated by the black circle. Note that the model range results from the combined influences of natural variability and human-caused climate change. The model data are from Rodgers et al. (2021) and the observational data are from Berkeley Earth Surface Temperature. Source: National Center for Atmospheric Research.

12 Key Message 3.6. Extreme Event Attribution

The science of evaluating the effects of human-caused climate change on extreme weather and climate events has advanced significantly. Human influence has changed the frequency and intensity of some types of extreme events, and it is now possible to quantify climate change effects on specific extreme events. (*High Confidence*).

Extreme event attribution quantifies the human influence on severe weather events, primarily through changes in magnitude and frequency (NASEM 2016). Recent methodological advances have widened the classes of weather events analyzed (Herring et al. 2022, 2019, 2018; Wehner et al. 2019). Confidence in attribution statements is increased when multiple methods, observations, and models lead to similar conclusions (Otto et al. 2020) and similar underlying trends are detected (Knutson 2017).

Recent methodological advances include graphical methods to identify cause and effect pathways (Ebert-Uphoff and Deng 2015), using physical insight to inform statistical models (Risser et al. 2022, 2021), “storyline” simulations (Shepherd 2016), and large ensembles (van der

Wiel et al. 2019). The CMIP5/6 databases are often used in event attribution studies, but the relative coarseness of the model grids (100 km or more) limits applicability to large-scale events such as certain heatwaves (Stott et al. 2004) and winter storms (Kam et al. 2022). Finer-scale events such as intense storms are often amenable to storyline hindcast simulations using higher resolution regional models to compare the “storm that was” with observed climate change to the “storm that might have been” without the human changes to the climate system (Pall et al. 2017; Takayabu et al. 2015). However, by construction, such storyline analyses inform attribution statements about changes in the magnitude of an event, not the frequency.

Attribution methods have advanced such that rapid statements can be made just weeks after an event (Philip et al. 2021; van der Wiel et al. 2017) and even forecasted (Reed et al. 2020), and these could be made operational (Wehner and Reed 2022). Despite recent progress, the human influence on some extreme weather events may not be attributable because of model limitations (van Oldenborgh et al. 2022, 2021).

Extreme event attribution has shown that some extreme events are happening with greater frequency and magnitude due to anthropogenic climate change. For example, climate change made a 2016 extreme precipitation event in Louisiana heavier and more likely (van der Wiel et al. 2017) and increased both precipitation (Risser and Wehner 2017; van Oldenborgh et al. 2017; Wang et al. 2018) and flooding (Wehner and Sampson 2021) during Hurricane Harvey. While these studies reveal how climate change affects extreme events, they also reveal that historical observations of climate are insufficient for characterizing future risks.

Key Message 3.7. Observations for Improving Process Understanding and Modeling

Recently deployed observing systems have reduced uncertainty in climate projections and improved our understanding of the climate system. Important advances in understanding stem from the application of new techniques that synthesize information from models and both new and existing observation networks and new data on past climatic conditions. (*High Confidence*).

Advances in Observations

New Earth-focused observations promise a deeper understanding of the Earth system and reduced uncertainty in climate projections. Combined with new process-oriented metrics and diagnostics (e.g., Maloney et al. 2019; Simpson et al. 2020; Leung et al. 2022), observations can enhance the validation of Earth system models. Recent NASA missions include the Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) thermal imager, focused on vegetation temperature and response to climate stressors; the Global Ecosystem Dynamics Investigation (GEDI) ecosystem lidar, focused on the forest canopy; and the Earth Surface Mineral Dust Source Investigation (EMIT) spectrometer. Other forthcoming missions include Time-Resolved Observations of Precipitation structure and storm

Intensity with a Constellation of Smallsats (TROPICS) and Joint Polar Satellite System-2 (JPSS-2), focused on tropical cyclones and other extreme weather events. Additional frontiers in satellite-based climate monitoring include both hydrological (e.g., snow thickness) and atmospheric (e.g., clouds and atmospheric composition) properties. Besides satellite observations, NASA Jet Propulsion Laboratory's Airborne Snow Observatory (ASO) and its commercial successor have performed numerous snow surveys, enabling extremely detailed maps of mountain snowpack. Also, recent efforts by USGS on the Next Generation Water Observing System (NGWOS) are enhancing the quality of real-time data on water quantity and quality from fixed and mobile instruments.

Emergent Constraints on Future Projections

Emergent constraints are a leading technique to reduce uncertainty in climate change projections (Eyring et al. 2019). The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship. Observations of the current climate are used to quantify model bias and constrain the future climate parameters. Research on emergent constraints has targeted a wide variety of geophysical processes (Hall et al. 2019). For example, projections of western US runoff in CMIP5 models can be constrained by the sensitivity of runoff to precipitation in the historical climate (Lehner et al. 2019). Future summer warming over the central US in CMIP5 models can be constrained by the temperature bias in the same region in the historical climate (Lin et al. 2017), and model bias in the intertropical convergence zone has been used to constrain projections of California winter precipitation (Dong et al. 2021b).

Key Message 3.8. Water Cycle Changes

Many processes relevant to the water cycle have already begun to change and are projected to continue changing as the planet warms, including atmospheric moisture (*high confidence*), atmospheric circulation, patterns of natural variability (*medium confidence*), and the modulating role of vegetation on evaporation (*low confidence*).

These drive changes in the intensity of precipitation in extreme events; snowfall, snowpack, snow melt; and the seasonal cycles of average precipitation and evaporation.

Seasonal and annual average precipitation and evaporation patterns have been changing with global warming. Precipitation from extreme events is projected to increase with warming (e.g., Neelin et al. 2017). It constitutes a large fraction of total precipitation, and thus also a large fraction of the change in precipitation. This can have counterintuitive results, such as increases in extreme precipitation but decreases in annual average precipitation in the same location (Figure 3.8; Pascale et al. 2017, 2018).

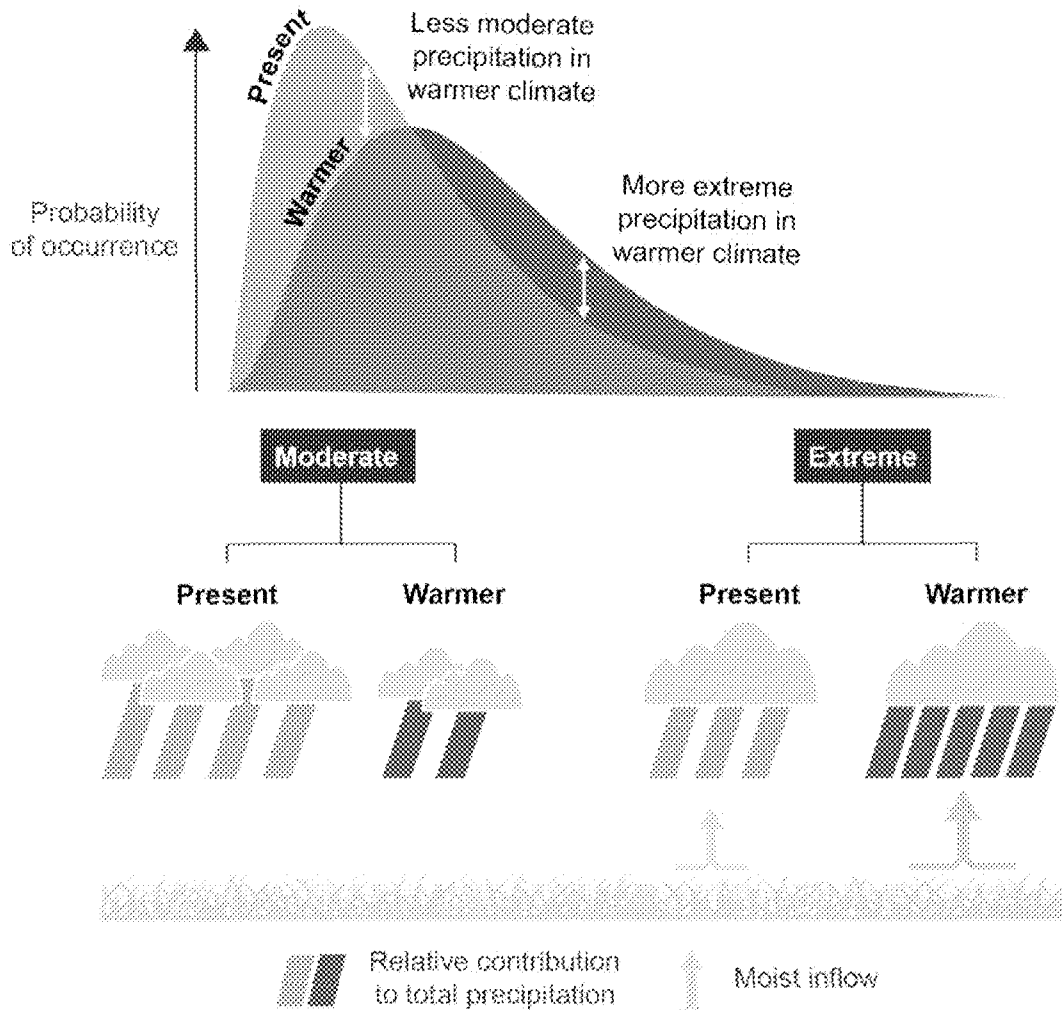
The relationship between extreme and total precipitation is determined by the overall variability. Total precipitation variability is projected to increase at all timescales and in most locations. This

1 implies increases in both heavy precipitation extremes and drought (Ukkola et al. 2020), a
2 phenomenon called whiplash (Swain et al. 2018).

3 Water vapor factors into the intensity of precipitation extremes, such that increased water vapor
4 alone would drive relatively uniform projected increases in precipitation extremes over much of
5 the planet. Additionally, changes in circulation modulate the spatial pattern of extreme
6 precipitation intensity change, increasing it in some regions and dampening it in others (Pfahl et
7 al. 2017). For extratropical cyclones in summer, precipitation intensity increases, and more
8 energetic convective storms are projected despite weakening circulation (Gertler and O’Gorman
9 2019). While understanding of these changes in extreme precipitation has improved, recent work
10 has also highlighted the oftentimes large magnitude of natural variability in extreme precipitation
11 (KM 3.5).

1 Figure 3.8. Anthropogenic Changes in Average and Extreme Precipitation

Changes in the Contributions of Moderate and Extreme Events to Total Precipitation With Warming



2
 3 CAPTION: Example changes in the precipitation distribution at many locations in climate models. (Top)
 4 In general, warming shifts the distribution towards a greater likelihood of large events, and a reduced
 5 likelihood of light-to-moderate events, with only a modest change in the average precipitation. (Bottom)
 6 Greater levels of water vapor in the atmosphere in a warmer world drive more precipitation during
 7 storms, when moist air masses converge. The increased water vapor convergence in very stormy areas
 8 also transports more water vapor out of surrounding areas, reducing any light to moderate precipitation
 9 there. The changes in average precipitation are often modest, because they reflect this tug-of-war
 10 between opposing changes in heavy and light-to-moderate precipitation. Changes in circulation can also
 11 affect the changes in all parts of the precipitation distribution. Certainty in projected changes differs
 12 among the underlying processes; the increase in water vapor and associated increase in extremes is very

certain, while the changes in circulation are less certain. Sources: Cornell University and University of California, Los Angeles.

Changes in precipitation seasonality can occur with or without changes in average annual precipitation. While one may expect increases in the amplitude of the precipitation seasonal cycle as precipitation increases proportionally to its present-day seasonal cycle, other changes in the seasonal cycle of precipitation have also been found. Examples of these changes include a sharpening of the seasonal cycle in California (Swain et al. 2018; Dong et al. 2019; Luković et al. 2021), a substantial increase in late-spring and a substantial decrease in late-summer precipitation in the US Midwest (Zhou et al. 2022a), and a delayed onset of rainfall in many monsoon regions (Song et al. 2018a, 2021).

One concern is that evaporation will increase with warming, leaving the land surface drier. In addition to changing evaporation from soil, plants also influence total evaporation through competing effects. In response to increased atmospheric CO₂ concentrations, plant stomata do not need to open as much to take in CO₂ for photosynthesis, which can reduce the amount of water they lose through transpiration, which would decrease total evapotranspiration (Swann et al. 2016). Conversely, an overall increase in the amount of vegetation that grows can amplify evaporative losses and surface drying (Mankin et al. 2019; Ukkola et al. 2016; Wang et al. 2022). It is not yet clear which of these mechanisms will predominate, although model projections and observational analyses for the United States suggest that the net effect will be for warming to increase evaporation and surface drying in much of the country (Mankin et al. 2017; Cook et al. 2020, 2021; Williams et al. 2020, 2022).

Snowpack in many mountainous regions of the US has already decreased on average over the last few decades; for example, the western US snowpack-driven reservoirs are already exhibiting changes (Mote et al. 2018). These declines are expected to be exacerbated by greater increases in winter temperatures compared to summer temperatures in some regions due to snow albedo feedbacks. Another factor that decreases snowpack is the larger temperature increases at higher altitudes, which increases the frequency of multiyear snow droughts (Marshall et al. 2019). Decreases in streamflow have also been observed and projected because of the increase in evaporation with warmer temperatures (Woodhouse et al. 2016; Milly and Dunne 2020; Lehner et al. 2017).

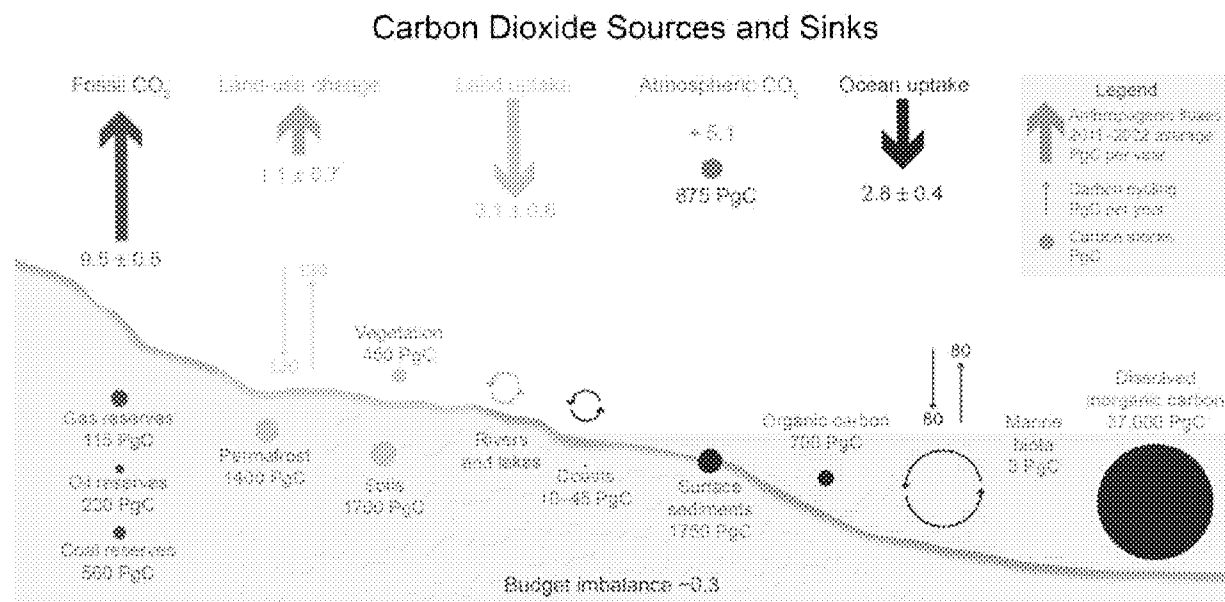
Key Message 3.9. Changes in the Carbon and Biogeochemical Cycles

Understanding of the biogeochemical responses to human-caused greenhouse gas emissions has increased due to expanded observations and improvements in models, but uncertainty in the future evolution of the global carbon cycle remains high (*high confidence*).

Terrestrial ecosystems and the oceans take up a little more than half of the CO₂ emitted from human activities, partially offsetting the climate effects of carbon emissions. From 2011 to 2020, annual emissions averaged 10.6 ± 1.2 PgC, and the emitted carbon was ultimately distributed

between the atmosphere (47%), vegetation and soils in terrestrial ecosystems (29%), and the oceans (24%) (Figure 3.9; Friedlingstein et al. 2022). Over the past six decades, the average fraction of anthropogenic CO₂ emissions that has accumulated in the atmosphere has remained nearly constant at 41%, even as fossil fuel emissions have rapidly increased.

Figure 3.9. Carbon Dioxide Sources and Sinks



6/24/2024 Joint Carbon Project

CAPTION: The primary sources of anthropogenic carbon are fossil fuel and land-use change emissions (upward arrows). While the land biosphere and ocean continue to take up the same proportion of anthropogenic carbon every decade (downward arrows), atmospheric CO₂ levels continue to increase because of the anthropogenic carbon that remains in the atmosphere. Represented here is the overall perturbation of the global carbon cycle averaged globally for the decade 2011–2020, with flux estimates from Canadell et al. (2021). Adapted from Friedlingstein 2022.

An important question is whether the same fraction of fossil fuel emissions will continue to be offset by ocean and land biosphere uptake, or whether the offset will slow or reverse over time. Answering this question depends on understanding feedbacks between the carbon cycle and climate change. The additional carbon sink on land is a consequence of increased vegetation productivity due to CO₂ fertilization (Chen et al. 2022) and forest regrowth after disturbances such as land clearing for agriculture (Pugh et al. 2019). Ocean waters take up an increasing amount of carbon due to chemical dissolution of CO₂ in seawater and biological fixation through photosynthesis and shell formation in some organisms, and subsequent transport of carbon into deeper waters.

As atmospheric CO₂ increases, plant productivity and soil carbon also increase and are partly responsible for increases in land carbon storage, which functions as a negative feedback on climate change. However, several processes could reduce terrestrial carbon uptake, including

1 increasing temperature and drought frequency or intensity, limitation of other necessary
2 nutrients, and land-use changes such as deforestation. In the Arctic, potentially large biogenic
3 releases of CO₂ and CH₄ to the atmosphere due to permafrost thaw, the timing of which may be
4 accelerated by increasing wildfire at high latitudes (Chen et al. 2021), could be a potentially
5 large positive climate feedback that may alter the effectiveness of climate mitigation strategies
6 (Bruhwiler et al. 2021). ESMs predict a total loss of near-surface permafrost by 2100 for
7 intermediate (RCP4.5) and very high(RCP8.5) emissions scenarios, and permafrost carbon
8 emissions are projected to outpace increased carbon uptake from higher vegetation productivity
9 in a warmer Arctic (Miner et al. 2022).

10 Uptake of CO₂ by oceans leads to acidification of seawater (Ch, 10). Over time, uptake of carbon
11 could slow as ocean waters become saturated with dissolved CO₂ (Heinze et al. 2015). Recent
12 observations show that ocean carbon processes are starting to change in response to the growing
13 ocean carbon sink, and these changes are expected to contribute to future weakening of the ocean
14 carbon sink under medium-to-high emissions scenarios (similar to SSP2-4.5 and SSP5-8.5 of
15 Figure 3.7 in Jiang et al. 2019; Schlunegger et al. 2020).

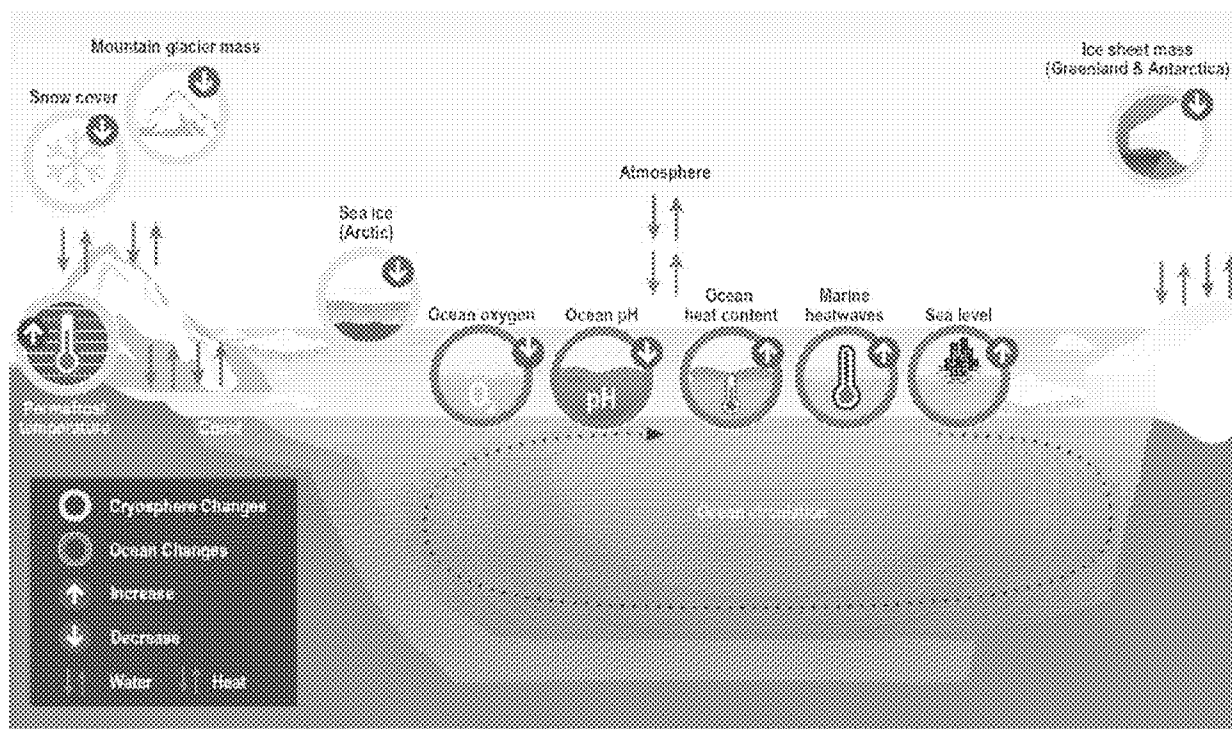
16 A comparison between the CMIP5 and CMIP6 generation of ESMs with respect to the
17 representation of the CO₂ fertilization effect and carbon cycle–climate feedbacks suggests that
18 uncertainties in these processes have remained large and virtually unchanged in recent years
19 (Arora et al. 2020). However, the latest generation of land models have improved representation
20 of biogeochemical cycles (Canadell et al. 2021), and ocean models have exhibited improved
21 representation of coupled physics and biogeochemical cycles (Séférian et al. 2020).

22 In the United States, the land carbon sink is dominated by forests, which have expanded in the
23 last century due to fire exclusion in the West and to secondary forest regrowth following
24 agricultural abandonment in the East. The growth of the North American forest biomass carbon
25 sink is expected to become more saturated and less effective over time (Zhu et al. 2018; Pugh et
26 al. 2019) (see CCB2). The climate change–wildfire relationship is also expected to play an
27 increasingly dominant role in the strength of the US land carbon sink, requiring increased
28 management of forests to meet carbon storage and other needs of society (Hessburg et al. 2021).
29 In addition, increasing temperature and moisture in some regions could lead to increased
30 microbial emissions of CH₄ from wetlands and Arctic tundra.

31 Key Message 3.10. Changes in Ocean and Cryosphere and Sea Level Rise

32 New observations, models and reconstructions have improved understanding of the drivers of
33 regional sea level rise (*high confidence*) and how processes combine to cause sea level
34 change at the coast (*medium confidence*).

Figure 3.10. Changes in Ocean, Cryosphere, and Coastal Processes



CAPTION: Processes in the ocean and cryosphere along with their linkages. Associated climate change—related effects, including sea level rise, increasing ocean heat content, ocean acidification, marine heatwaves, and ice mass loss, are also shown. Adapted from Box 1, Figure 1 of IPCC 2019.

Ocean

The ocean has a large capacity to store and release heat and is able to absorb 91% of the excess heat attributed to greenhouse gas emissions (Figure 3.10; Forster et al. 2021). The ocean moves heat from the tropics towards polar regions, where warm surface ocean waters transform into cooler, high-density waters that sink (Talley 2013), taking high carbon concentrations with them (Gruber et al. 2019). The Atlantic meridional overturning circulation (AMOC) is an important component of the global ocean circulation, transporting heat and carbon, and affecting hydroclimate, hurricane activity, and coastal sea level. It is hypothesized from some proxy evidence that the AMOC has declined since the Industrial Revolution (Caesar et al. 2018). It remains uncertain whether observations support the anthropogenically forced weakening of the AMOC during the past four decades predicted by climate models (Jackson and Wood 2020).

On short timescales (annual to decadal), ocean circulation dominates the pattern of changes in ocean heat content, although on longer time periods, the spatial pattern is primarily associated with the addition of excess heat into the ocean (Zanna et al. 2019). Since 2005, Argo profiling floats have provided observations of temperature and salinity changes in the global ocean to a depth of 2,000 meters. These measurements show an increase in global ocean heat content,

1 although there is geographic variability. On shorter timescales, marine heatwaves are periods of
2 extreme high ocean temperature relative to the long-term average seasonal cycle (Hobday et al.
3 2016). Persistent marine heatwaves have been observed in the northeastern Pacific since around
4 2014 (Di Lorenzo and Mantua 2016; Gentemann et al. 2017; Amaya et al. 2020) with associated
5 negative impacts on ocean ecosystems (Ch. 27).

6 **Cryosphere**

7 The cryosphere is the frozen part of the Earth system and includes ice sheets, glaciers, sea ice,
8 permafrost, and snow (Figure 3.10). Observations of the cryosphere have expanded in recent
9 years, including from satellites like Gravity Recovery and Climate Experiment Follow-On
10 (GRACE-FO) and Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2). These and other
11 complementary observations of the cryosphere show declines in ice sheet and glacier mass, snow
12 cover, and Arctic sea ice (Fox-Kemper et al. 2021). Through efforts like the Ice Sheet Mass
13 Balance Intercomparison Exercise (IMBIE; The IMBIE Team 2020), there is clear evidence of
14 loss of ice sheet mass from 1993 to 2020, and the rate of loss has increased for both the
15 Greenland and Antarctic ice sheets. There is increased consensus regarding the behavior of many
16 ice sheet processes. However, as the climate warms, the future response of the ice sheets and
17 some associated processes are still uncertain (Fox-Kemper et al. 2021). Two specific processes,
18 marine ice cliff instability (Deconto and Pollard 2016; Deconto et al. 2021) and marine ice sheet
19 instability (Joughin et al. 2014; Waibel et al. 2018; Hoffman et al. 2019; Robel et al. 2019;
20 Morlighem et al. 2020), could lead to rapid ice sheet loss over several decades, but the physical
21 processes that would result in these instabilities and how they would progress once triggered
22 remain uncertain. The decline in sea ice impacts several critical functions: sea ice serves to
23 regulate climate by reflecting solar radiation, inhibits ocean–atmosphere exchange of heat,
24 momentum and gases, supports global deep ocean circulation, polar species, and livelihoods of
25 people in the Arctic.

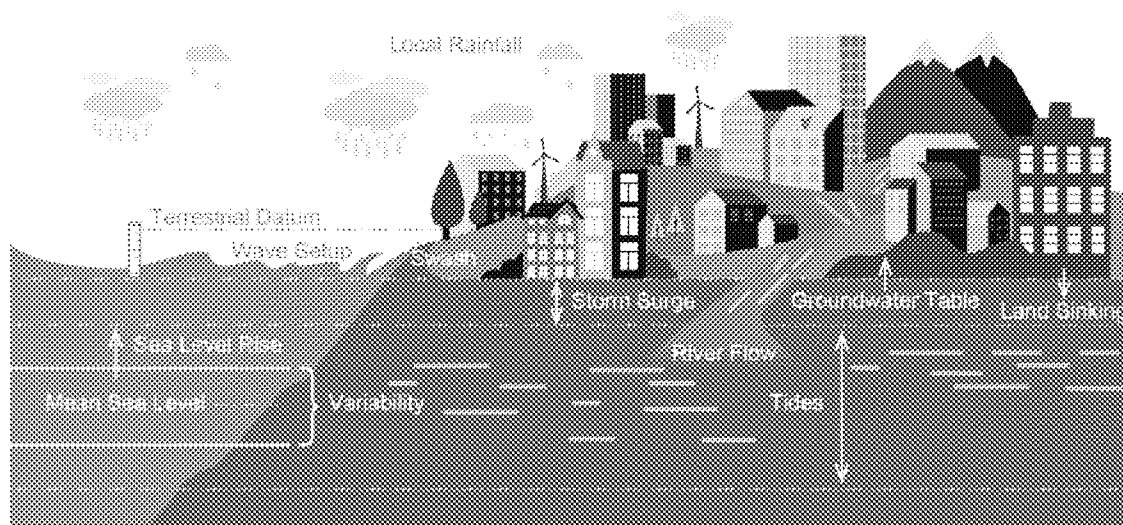
26 **Sea Level Rise**

27 Over multidecadal to centennial timescales, the primary drivers of changes in global mean sea
28 level (GMSL) are thermal expansion due to heating of the ocean and the addition of water mass
29 associated with losses from ice sheets and glaciers. Other changes in the movement of water
30 between ocean and land, including from groundwater depletion and water impoundment (water
31 stored behind dams), have a secondary impact on GMSL, although they can increase in
32 importance for certain time periods (Frederikse et al. 2020). During the 20th century, changes in
33 GMSL estimated from tide-gauge records have been explained by the individual processes
34 contributing to it (Frederikse et al. 2020). More recently, changes in GMSL observed from
35 satellite altimetry have been explained using the in situ measurements of the Argo profiling
36 floats and the observations of water-mass change from the GRACE and GRACE-FO
37 satellites. As seen in both tide gauge and satellite records, the rate of GMSL rise has been

1 increasing, driven by accelerating contributions from the underlying processes (Nerem et al.
 2 2018; Dangendorf et al. 2019; Frederikse et al. 2020).

3 **Figure 3.11. Coastal Flood Exposure**

Physical Factors Directly Contributing to Coastal Flood Exposure



4
 5 CAPTION: Schematic showing physical factors affecting coastal flood exposure. Due to the clear and
 6 strong relative sea level rise signal (i.e., combination of sea level rise and sinking lands), the probability
 7 of flooding and impacts are increasing along most US coastlines. Source: Sweet et al. 2022.

8 Sea level rise is not uniform across the globe; rather, it manifests as relative sea level rise that
 9 also responds to key factors important at regional and local scales (Kopp et al. 2014; Sweet et al.
 10 2017; Hamlington et al. 2020; Fox-Kemper et al. 2021). On short timescales and in short records,
 11 natural variations on interannual to decadal timescales can affect estimates of rates and
 12 accelerations. On long timescales, however, there are three primary causes of regional variations
 13 in relative mean sea level: 1) sterodynamic changes (the combination of thermal expansion and
 14 ocean dynamics); 2) gravitational, rotational, and deformational changes that result from water
 15 moving from the cryosphere to the ocean; and 3) vertical land movement (subsidence or uplift)
 16 due to glacial isostatic adjustment, tectonics, sediment compaction, groundwater and fossil fuel
 17 withdrawals, and other non-climatic factors (Gregory et al. 2019; Sweet et al. 2022).

18 An improved understanding of the drivers of regional mean sea level rise and how processes
 19 combined to cause sea level change at the coast has led to better assessments of the frequency,
 20 duration, and timing of high-water level and coastal flooding events (Figure 3.11; Sweet et al,
 21 2022). Regional sea level change has been the main driver of changes in extreme water levels.
 22 Due to ongoing regional relative sea level rise and narrowing of the gap between the typical high
 23 tide and flooding threshold, the frequency of high-tide flooding has increased. Natural ocean
 24 variability, including that associated with tides and large-scale climate signals that did not
 25 necessarily result in flooding in the past, are expected to lead to a rapid increase in the amount of

high-tide flooding in the coming decades when combined with future sea level rise (see Ch. 9; Yin et al. 2020; Thompson et al. 2021; Sweet et al. 2022).

Key Message 3.11. Atmospheric Circulation Changes

Atmospheric circulations that affect US regional climate are influenced by the global warming–induced expansion of the tropics (*medium confidence*). However, identifying the relative contributions of natural variability and human-induced climate change to changes in regional atmospheric circulation remains challenging

Past and future changes in regional climate of the United States are strongly modulated by atmospheric circulation features such as the semi-permanent North Pacific and North Atlantic subtropical high-pressure systems, the Aleutian Low, the meandering jet stream stretching from the North Pacific to the North Atlantic, extratropical storm tracks and fronts, and the North American monsoon. These regional- to continental-scale circulation features are in turn modulated by even larger-scale overturning circulations such as the Hadley cell (see CSSR Ch 5; Perlwitz et al. 2017). Regional circulation features over North America are also modulated by recurring patterns of variability such as the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) and by variability due to the chaotic dynamics within the atmosphere.

A major challenge in climate science is to separate contributions of inherent variability from anthropogenic forcing on regional atmospheric circulation changes. Broadly speaking, anthropogenic forcing alters the vertical and horizontal energy and moisture distribution in the atmosphere. Atmospheric circulation is directly impacted by the resulting changes in the temperature gradient from the equator toward the poles (both in the lower and upper troposphere), the decrease in the rate that temperature falls with increasing height above the surface, and increased latent heating.

A synthesis of observational and modeling studies estimates that the tropics have widened by about 0.5° of latitude per decade since 1979. Although climate models driven by external forcing simulate on average a larger expansion rate than observed, the observed rate is within the bounds of the model simulations (Staten et al. 2018). Discrepancy between the observed and simulated rates is partly due to patterns of natural variability such as ENSO and the Pacific Decadal Oscillation as well as natural atmospheric variability (Grise et al. 2019; Simpson 2018).

Consistent with the tropical expansion, climate models project poleward shifts of the jet streams and storm tracks and poleward expansion of the subtropical dry zones with warming (CSSR Ch. 5). However, the northern hemisphere jet shifts are regionally and seasonally dependent (e.g., Oudar et al. 2020; Zhou et al. 2022b). Simulations show a poleward jet shift in the central North Pacific with warming, along with an eastward jet extension that steers more Pacific storms towards California (Neelin et al. 2013). However, large uncertainty remains because the jet extension is also influenced by natural variability (Dong et al. 2021a). With global warming shifting the North American westerly jet poleward throughout the warm season, climate models

project late-spring wetting and late-summer drying in the Midwest (Zhou et al. 2022a). Poleward expansion of the North Atlantic subtropical high may intensify and extend the Great Plains low-level jet poleward, affecting warm-season precipitation in the Midwest (Song et al. 2018b). Besides changes connected to the tropical expansion, climate models project a weakening of the North American monsoon with warming due to increased atmospheric stability (Pascale et al. 2017). Similar to other monsoon systems, the onset of North American monsoon rainfall is projected to be delayed by warming (Cook and Seager 2013; Song et al. 2018a, 2021). In the North Pacific, warming is projected to reduce the frequency of atmospheric blocking during winter (Davini and D’Andrea 2020).

Key Message 3.12. Changes in Extreme Events

Human activities are affecting climate system processes in ways that are expected to increase the frequency and intensity of many, but not all, climate extremes, including heat waves, wildfires, drought, heavy rainfall, and coastal flooding (*medium to high confidence*).

Extreme Heat and Cold

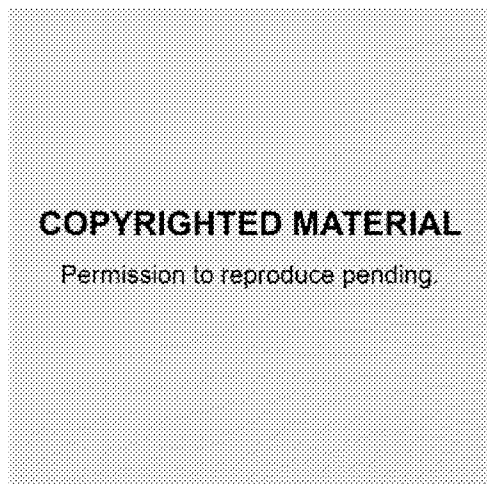
Changes in temperature extremes in recent decades are driven primarily by trends towards warmer conditions (“mean shifts”) rather than any changes in variability (Baldwin et al. 2019). Consequently, the frequency and intensity of cold extremes has declined over much of the United States while the frequency and intensity of extreme heat has increased (Sheridan and Lee 2018). Warming may also be driving increases in the occurrence and persistence of circulation anomalies that give rise to extreme cold and heat (Cohen et al. 2021), though the evidence that these mechanisms have played a role in recent events is mixed (Barnes and Screen 2015). Climate change may also be contributing to “false spring” events (Chamberlain et al. 2021), where early warming has caused early budbreak and flowering of plants, exposing them to damaging frost and freeze events (Richardson et al. 2018).

Extreme Precipitation and Flooding

Observed increases in extreme precipitation intensity at the continental scale in North America have been, for the first time, attributed to human influence (Kirchmeier-Young and Zhang 2020). With warming, it is expected, and has been documented, that more winter precipitation will fall as rain instead of snow (Kliver and Leathers 2015), though the projected intensity of most extreme snowstorms remains uncertain (Zarzycki 2018). Projected future increases in extreme precipitation events are larger in the winter season since warming in winter is larger, including events related to atmospheric rivers (Payne et al. 2020). Sea surface temperature increases drive increases in tropical cyclone duration and intensity, and these dynamic changes can result in extreme precipitation increasing at rates higher than the increase in atmospheric water vapor (Patricola and Wehner 2018). Where and when increases in extreme precipitation manifest in any given year or even decade is strongly subject to natural variability (see also KM 3.8). Notably,

increases in extreme precipitation events do not always directly translate to increases in river flooding, in part because of the myriad of other processes at the land surface that affect flood risk (Figure 3.12).

Figure 3.12. Key Processes That Can Cause or Prevent Disastrous River Floods

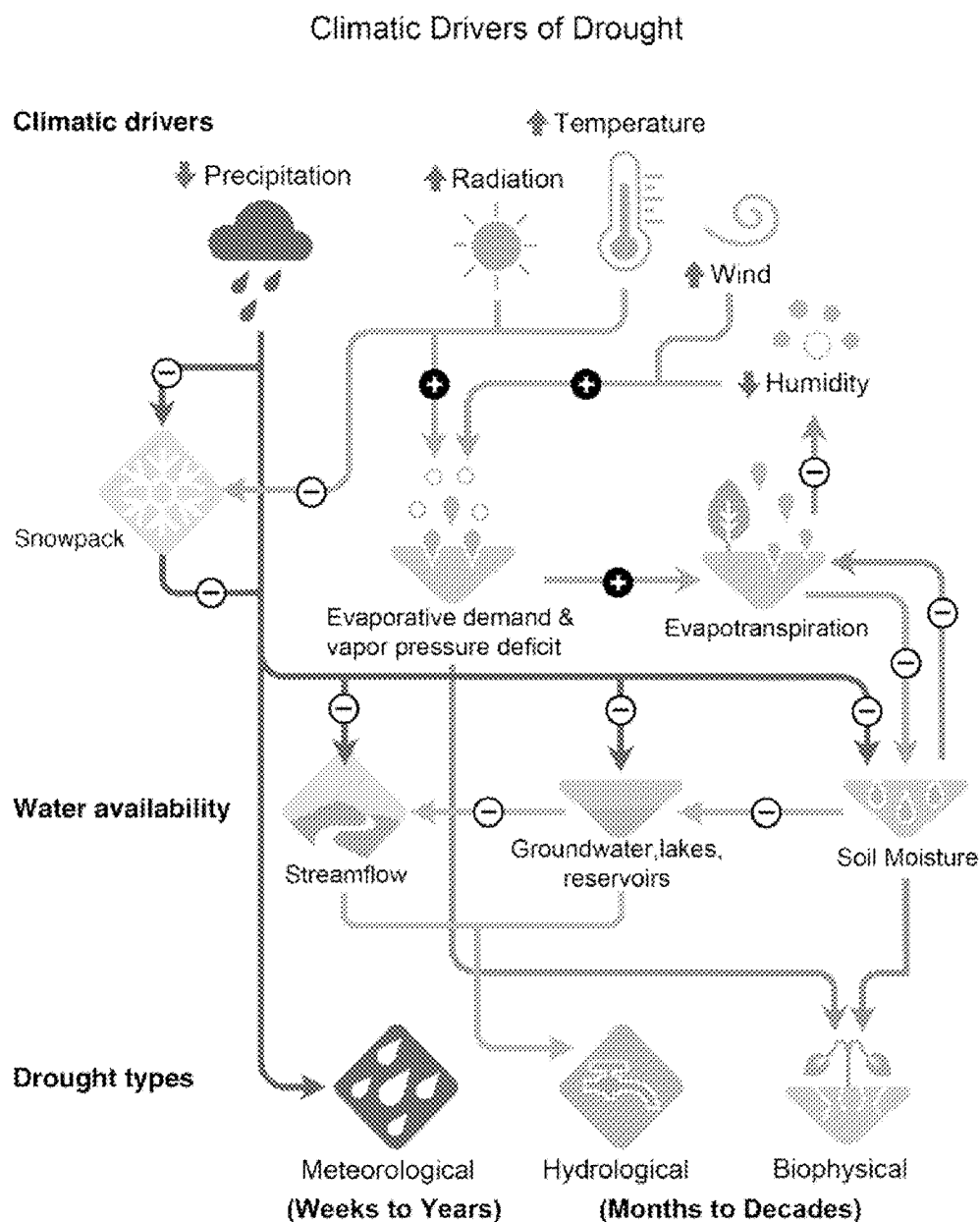


CAPTION: Atmospheric, catchment, and river network processes interact to cause high river flood levels (hazards as blue symbols). The impacts (orange symbols) of flood events depend on the exposed population and assets in flood-prone areas (exposure as red symbols), and on their susceptibility when hit by a flood (vulnerability as purple symbols). Indirect impacts can occur in regions far away from the inundated areas, for instance, owing to global supply chain disruptions. Adapted from Figure 1, Merz et al. 2021.

Drought

Drought is broadly defined as a transient period of below-average water availability, typically expressed in terms of fluctuations in precipitation, soil moisture, or streamflow and runoff (Wilhite and Glantz 1985). Drought is a complex phenomenon (Figure 3.13) that depends on fluctuations in moisture supply, direct losses of moisture to the atmosphere, and important ecosystem and land surface processes (Cook et al. 2018; Swann 2018; CSSR Ch. 8, Wehner et al. 2017). Western North America experienced several decadal-scale droughts during the 20th century (Fye et al. 2003) and numerous multidecadal “megadroughts” prior to AD 1600 (Cook et al. 2016), and is currently experiencing an ongoing megadrought largely unprecedented over the last 1,200 years (Williams et al. 2020, 2022).

1 Figure 3.13. Climatic Drivers of Drought, Effects on Water Availability, and Impacts



2
3 CAPTION: Changes in climatic drivers (e.g., precipitation, temperature, wind, etc.) affect different
4 aspects of the hydrologic cycle (e.g., evapotranspiration, snowpack, streamflow, soil moisture, etc.). In
5 turn, these hydrologic shifts translate into changes in the severity, frequency, and risk of different
6 drought types. Plus and minus signs denote the direction of change in the driver that would cause
7 increases in drought. For example, where precipitation declines (down arrow), all drought types will
8 increase because this reduces snowpack, streamflow, groundwater and reservoir storage, and soil
9 moisture. Similarly, increasing temperatures (up arrow) are also likely to increase hydrological and
10 biophysical drought by reducing snowpacks and increasing evaporative losses from streams, surface
11 reservoirs, and soils. Adapted from Figure 8.6 of Douville et al. 2021.

Projected precipitation changes in response to climate change are highly season- and region-dependent over the United States, especially in the West (Marvel et al. 2021). Climate change is therefore expected to amplify drought, primarily through warming-induced increases in evaporative demand and surface water losses (Cook et al. 2020, 2021) and declines in snowfall and water stored in winter snowpack (Siirila-Woodburn et al. 2021). There is strong evidence that these processes are already amplifying drought severity in California (Griffin and Anchukaitis 2014; Williams et al. 2015; Berg and Hall 2017), the Pacific Northwest (Marlier et al. 2017; Mote et al. 2016), the Colorado River basin (Milly and Dunne 2020; Xiao et al. 2018), and across southwestern North America (Williams et al. 2020). However, there are uncertainties in how these processes may present in the future. For example, changes in plant water use in response to increasing temperatures and rising atmospheric CO₂ are complex and poorly understood, and may either ameliorate (Swann 2018) or amplify (Mankin et al. 2019) soil moisture and runoff droughts at the surface.

Wildfire

The direct influence of climate change on modern and future wildfire activity arises from the effect of warming on fuel moisture content and flammability (Focus on Western Wildfires). Flammability is related directly to the vapor pressure deficit (VPD), an integrative measure of atmospheric aridity or dryness. High VPD is strongly associated with the hot and dry weather conditions conducive to the intensification and spread of wildfires, as well as with drier fuels at the surface. In recent decades, warmer temperatures, declines in humidity, and increases in VPD have caused large-scale increases in fire weather (Abatzoglou et al. 2021a) and areas burned by wildfire (Abatzoglou and Williams 2016; Burke et al. 2021; Williams et al. 2019) across the West. From 1984 to 2015, about half of the increase in burned area across the western United States is attributable to increases in fuel flammability caused by anthropogenic climate change. These climate change-driven increases in wildfire burned area are expected to continue into the coming decades, as fuel availability is not expected to be a limiting factor before 2050 (Abatzoglou et al. 2021b).

1 **Figure 3.14. Consecutive Events Leading to and Resulting from Wildfires**



2
3 **CAPTION:** Consecutive events resulted in significant human health and economic impacts in Southern
4 California: a prolonged drought from 2012 to 2016; above-average winter precipitation in 2017,
5 enhancing growth of fuels; a dry, warm spring and summer, reducing moisture levels and drying existing
6 vegetation; record-setting Santa Ana winds; fires occurring shortly thereafter; and rainfall over the
7 burned area, leading to debris flow event in Montecito, CA. Adapted from Figure 1 of AghaKouchak et al.
8 2020.

9 **Compound Events**

10 Compound events refer to the combination of multiple weather or climate hazards—which
11 individually may not be extreme events—that pose risks to human or natural systems
12 (Zscheischler et al. 2020; Zhang et al. 2021; Seneviratne et al. 2021; see example in Figure 3.14)
13 and are described in further detail in Focus on Compound and Complex Events. Since climate
14 change may affect the frequency and magnitude of the individual components of compound
15 events in different ways, changes in compound events can be complex. Recent advances in
16 statistical techniques used to describe compound events (Cooley et al. 2019; Sadegh et al. 2017;
17 Donges et al. 2016; Boers et al. 2019) offer rigorous ways to quantify changes. Progress has also
18 been made in categorization of compound event types in this rapidly evolving field (Raymond et
19 al. 2020; Bevacqua et al. 2021; Zscheischler et al. 2020).

20 **Traceable Accounts**

21 **Process Description**

22 Team members were selected from two sources: 1) the pool of nominations received via the
23 public call for authors; and 2) candidates identified by the chapter lead author, federal
24 coordinating lead author, and agency coordinating authors from their extended networks and
25 recommendations they received. Considering the areas of expertise needed for the chapter as
26 summarized below, selections were made to ensure diverse representation across multiple axes.

- Long-lived and short-lived climate forcings and biogeochemical cycles (Vaishali Naik, NOAA Geophysical Fluid Dynamics Laboratory)
- Land use land cover change and biogeochemical cycles (Forrest M. Hoffman, DOE Oak Ridge National Laboratory)
- Climate response and internal variability (Clara Deser, National Center for Atmospheric Research)
- Scenario development and climate model diagnostic (Claudia Tebaldi, DOE Lawrence Berkeley National Laboratory)
- Climate feedbacks and response (Stephen Klein, DOE Lawrence Livermore National Laboratory)
- High resolution modeling and climate model diagnostics (Michael F. Wehner, DOE Lawrence Berkeley National Laboratory)
- Regional climate change (Alex Hall, University of California – Los Angeles)
- Climate model diagnostics and metrics (Paul A. Ullrich, University of California – Davis)
- Extreme event attribution and cryosphere (Sarah Kapnick, JP Morgan Chase & Co)
- Cryosphere and sea level rise (Benjamin D. Hamlington, NASA Jet Propulsion Laboratory)
- Precipitation variability and extremes (Angeline G. Pendergrass, Cornell University)
- Drought and paleoclimate (Benjamin Cook, NASA Goddard Institute for Space Studies)
- Hydrologic and heat extremes (Andrew Hoell, NOAA Physical Sciences Laboratory)

Key Message 3.1. Drivers of Climate Change

Description of Evidence Base

Evidence of human drivers of global warming is provided by identifying the human-induced components that perturb the Earth's energy budget and understanding how these have evolved over long timescales. Scientists have known the potential for climate change due to CO₂ emitted from human activities since the early 20th century and identified other human drivers, including non-CO₂ greenhouse gases, land-use change, and aerosols by the 1970s (Ramaswamy et al. 2019). Assessment of multiple lines of evidence, including proxy records, ice core records, and direct observations, provide unequivocal evidence of the role of human activities in increasing atmospheric levels of greenhouse gases and aerosols over the industrial era. For latest versions of long-term changes in greenhouse gas abundances, the reader is referred to figure TS.9 in the IPCC AR6 Technical Summary (Arias et al. 2021), which shows strong increase in well-mixed greenhouse gases since the 19th century that is exceptional over the long-term. Global average annual anthropogenic emissions of these gases reached the highest levels in human history over the recent measured decade based on assessment of multiple lines of evidence (Canadell et al 2021).

Human-induced emissions of greenhouse gases alter the atmosphere's radiative balance and lead to a climate response. Earth system model simulations reproduce global surface temperature trend only when human-induced climate drivers are included. Multi-model attribution experiments in support of the different phases of the Coupled Model Intercomparison Project (CMIP) have consistently shown the majority of the observed global warming to be human-induced, while that attributable to natural drivers is small (Eyring et al. 2021).

Major Uncertainties

Although there is a high confidence in the measured increases in atmospheric greenhouse gases since preindustrial times, attributing these increases to anthropogenic emissions or natural emissions is subject to some uncertainty (e.g., Saunio et al. 2020; Tans 2009). Fossil fuel emissions of CO₂ have the lowest uncertainty because of the direct relationship between combustion and emissions. Since radiocarbon (¹⁴CO₂) is absent in fossil fuels, measurements of atmospheric ¹⁴CO₂ suggest that CO₂ emission inventories based on fuel consumption are accurate to within at least 10% for the continental US, with larger differences found for smaller regions (Basu et al. 2022). However, there are discrepancies between different methods for quantifying CO₂ emissions and uptake related to land-use changes, the size of land uptake in the northern extratropics, and the strength of the ocean carbon uptake over the past decade (Friedlingstein et al. 2022). For land-use change, lack of historical land-cover information presents an important limitation. Likewise, inadequate coverage of datasets used to inform models of carbon exchanges between the biosphere and oceans and the atmospheric results in uncertainty for both process-based models and atmospheric inversions.

For CH₄ emissions and removals, uncertainties are potentially larger than for CO₂. Emissions of CH₄ are usually the result of unintentional leakage from oil and gas infrastructure or the result of microbial processes that result from agriculture, livestock, or waste treatment. This unintentional leakage makes quantifying emissions using inventory methods difficult. However, measurement of the stable isotope of CH₄ (¹³CH₄) imply that microbial sources are the primary drivers of recent atmospheric CH₄ growth. Measurements of ¹³CH₄ provide insight into sources because microbes prefer to use the lighter carbon isotope (¹²C) for metabolism, so an increase in microbial sources will mean isotopically lighter atmospheric CH₄.

Other important sources of uncertainty include difficulty in constraining atmospheric chemical destruction, and uncertainty in the distribution and processes determining natural emissions. Saunio et al. (2020) found that bottom-up estimates of emissions using inventories and emissions models appear to be overestimated in comparison with estimates from atmospheric inversions. Other studies using atmospheric observations of stable isotopes of CH₄ have suggested that global fossil fuel emissions are likely higher than those estimated by inventories (Schwietzke et al. 2016; Lan et al. 2021)

Description of Confidence and Likelihood

There is *very high confidence* that emissions of greenhouse gases have caused nearly all global warming observed over the industrial era” at the beginning of the paragraph. Observations clearly show unequivocally that concentrations of major greenhouse gases have increased in the atmosphere since preindustrial times. Uncertainties in natural chemical removals and emissions can be significant. However, these uncertainties are unlikely to change the central conclusion that anthropogenic emissions have caused the significant increases in greenhouse gases over the industrial period.

Key Message 3.2. Climate Sensitivity and Climate Feedback

Description of Evidence Base

The assessment of climate sensitivity and climate feedbacks follows that of Sherwood et al. (2020) and Forster et al. (2021), which were subject to review by peers and the community. In this Traceable Account, we provide a summary of the evidence base, major uncertainties, and a description of confidence and likelihood following these assessments. As also shown in Figure 3.3, the major change in these new assessments is to primarily base climate sensitivity estimates on observational data from multiple past periods combined with physical constraints, without directly using the values of climate sensitivity produced by climate models. Satellite observations of natural climate variability were used to provide global estimates of physical climate feedbacks (Dessler 2013; Ceppi and Nowack 2021) as well as the cloud feedbacks for individual cloud types (Klein et al. 2017; Williams and Pierrehumbert 2017; Vaillant de Guelis et al. 2018; Terai et al. 2016; McCoy et al. 2020). For many climate feedbacks, emergent constraints (Ceppi and Nowack 2021; Thackeray et al. 2021; Klein and Hall 2015) support the practice of inferring long-term climate feedbacks from short-term climate feedbacks inferred from observations of present-day natural climate variability. For changes between the preindustrial and present-day, temperature analyses of in situ data provide confident estimates of global mean temperature changes (Lenssen et al. 2019; Morice et al. 2021). Combining these temperature changes with estimates of effective radiative forcing for this period (KM 3.1) yields a preliminary estimate of climate sensitivity acting over the historical period. This preliminary estimate is now thought to be biased low to relative to the climate sensitivity for CO₂ doubling because climate feedbacks are sensitive to the pattern of sea surface temperature warming, and the pattern of warming in the historical period differs markedly from that expected for doubling of CO₂ (Andrews et al. 2015; Zhou et al. 2016). Inferring climate sensitivity from paleoclimate changes relies on accurate estimates of temperature and radiative forcing changes for well-studied stable periods in the past, such as the Last Glacial Maximum (~20,000 years ago, Kageyama et al. 2017), the Mid-Pliocene Warm Period (~3 million years before present, Haywood et al. 2016), and the Paleocene-Eocene Thermal Maximum (~56 million years before present, Lunt et al. 2017). To estimate a present-day climate sensitivity from paleoclimatic data, estimates of changes in temperature and radiative forcing must be derived from proxy data. It is

also necessary to consider how different ice sheet and continental configurations acted as forcing (Köhler et al. 2010) as well as the temperature dependence of climate feedbacks (von der Heydt and Ashwin 2016).

Synthesizing the implications for climate sensitivity from this extremely diverse body of evidence is non-trivial. Synthesis requires the development of a common framework to treat evidence based upon extensions to the forcing-feedback paradigm (Sherwood et al. 2015, 2020; Forster et al. 2021) as well as the sustained multiyear interaction of scientists from diverse research communities. Mathematical methods used in synthesis vary from complex Bayesian methods (Sherwood et al. 2020) to simpler consistency arguments (Forster et al. 2021).

Major Uncertainties

A major uncertainty in the estimate of climate sensitivity involves the pattern of sea surface temperature warming in the Pacific for the long-term forced response to CO₂ doubling (Sherwood et al. 2020). Over the last several decades, the observed pattern of warming has featured smaller warming or even cooling in the East Pacific, increasing the amount of low clouds and sunlight reflected back to space, and thereby dampening the warming of Earth. It is thought that this pattern in the recent past is due to natural climate variability. It is expected that over the 21st century, the warming in the East Pacific will catch up and exceed that in the West Pacific, matching the predictions of CMIP models for CO₂ dominated warming. However, if the observed recent pattern of warming includes a component of the forced response to CO₂ which models fail to predict, then climate sensitivity values at the high end are less likely.

Other key climate sensitivity uncertainties (Sherwood et al. 2020) include: 1) the scaling ratios between feedbacks estimated from the smaller short-term temperature variability and the larger climate change expected in the 21st century, 2) the cloud feedbacks from cloud types other than the well-studied marine low clouds, 3) the magnitude of aerosol forcing over the historical period, knowledge of which is critical for determining the component of historical warming from greenhouse gases, 4) the abundance of dust and other aerosols in the Last Glacial Maximum, 5) the characterization by proxy records of temperature, trace gases, and other forcing agents for warm periods in the deep geological past, 6) the dependence of climate sensitivity on the background state, and 7) the accounting for Earth system effects when interpreting the consequences of the paleo-record for a climate sensitivity applicable to 21st century warming.

Description of Confidence and Likelihood

Confidence is *high* in the reduced range of climate sensitivity because its observational estimates are derived from three independent lines of evidence and the three central estimates of climate sensitivity are in general agreement. The three lines of evidence are that from 1) natural climate variability in the present day, 2) the changes in climate from the preindustrial period to the present day, and 3) the changes in climate from various cold and warm periods in the paleoclimate record. Additional reasons for high confidence include a greater understanding of

how physical climate feedbacks vary with the nature of changes for different timescales, and a greater ability to synthesize diverse evidence from different periods in Earth's past.

Key Message 3.3. Changes at Regional Scales

Description of Evidence Base

It has been well established since the earliest climate change assessments that the local climate change response in a particular variable can differ substantially from the globally averaged response in that same variable. For the latest versions of the geographical distributions of the climate change response to anthropogenic forcing, and the corresponding globally averaged response, the reader is referred to examples seen in Figures SPM.5, SPM.8, TS.6 of the IPCC Sixth Assessment report (IPCC 2021; Arias et al. 2021). Such figures are qualitatively similar to the analogous figures from previous IPCC assessments. In the last decade, there has been increasing recognition of the large role of regional-scale natural variability in the future evolution of climate, and the fact that regional natural variability signals can be competitive with forced anthropogenic signals (e.g., Deser 2020). The mechanisms by which the climate system generates such large levels of natural variability are well documented and understood. Examples of well-understood and documented modes of variability relevant to North American climate include ENSO, the Pacific Decadal Oscillation, the Pacific North American pattern, and the northern annular mode. Many of these patterns have limited predictability beyond a timescale of about 2 weeks, leading to an irreducible uncertainty in the actual evolution of climate. A particularly important caveat to this statement relates to the ENSO phenomenon, which has some seasonal to interannual predictability. We also note that modes of variability themselves can also be affected by anthropogenic forcing, and these signals may be predictable. (Lee et al. 2021). The idea of irreducible imprecision applies to future projections only. It is not meant to cast doubt on anthropogenic climate change that has already been detected in the observational record despite natural variability (Seneviratne et al. 2021; Eyring et al. 2021).

Major Uncertainties

Although the idea that the regional climate change response differs from the globally averaged response is not controversial, there remain major uncertainties in the magnitudes of the climate change response at any given location. This reflects large differences in local outcomes across the global climate model (GCM) projections, as well as large differences in the local response when those GCMs are downscaled to higher resolution. In addition, because of the limited duration of the observational record, the magnitude of natural variability on timescales longer than roughly a decade is not well constrained. For example, we cannot exclude the possibility that the true natural variability of the climate system is larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

Description of Confidence and Likelihood

Because of the widespread agreement across generations of climate scientists that the local climate change response in a particular variable can differ substantially from the globally averaged response in that same variable since the earliest climate change assessments, there is *very high confidence* in this statement. Because the mechanisms by which the climate system generates large levels of natural variability all over the globe are well documented and understood, there is also *very high confidence* in the statement that natural climate variability limits the precision of regional-scale projections.

Key Message 3.4. New Scenarios and Climate Projections

Description of Evidence Base

The development of the set of new scenarios used by CMIP6 by the so-called parallel process (Moss et al. 2010) started while the CMIP5 simulations based on the representative concentration pathways (RCPs) were produced, analyzed, and assessed in IPCC 2013 (the stage setting essay for the new scenarios development is Ebi et al. 2014). The new scenarios are based on plausible future alternative pathways of socioeconomic development (the SSPs) from which consistent GHG emissions trajectories unfold, as opposed to simply consisting of idealized trajectories of future GHGs. Idealized trajectories (like 1% annual increase in CO₂ concentrations, or an instantaneous doubling of CO₂ concentrations) are useful sensitivity experiments, but they cannot be considered plausible, being decoupled from assumptions about human-caused emissions. About 40 modeling centers from all over the world participated in CMIP6 and ScenarioMIP (Tebaldi et al. 2021).

Major Uncertainties and Research Gaps

Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that the highest scenario, SSP5-8.5 is no longer plausible, without a reversal of current trends in the adoption of renewables and energy efficiency. The scenario development community is always testing the structural uncertainties of integrated assessment models, and therefore the assumptions that produce the alternative emission pathways. Timely updates of the baseline from which future projections are made, on the basis of current trends and observations of emissions, are necessary to maintain the plausibility of alternative pathways.

Description of Confidence and Likelihood

The section is a description of factual results, so confidence and likelihood do not apply.

1 Key Message 3.5. Large Ensemble Simulations

2 Description of Evidence Base

3 The Key Message and supporting text summarize evidence documented in the climate science
4 peer-reviewed literature. About a decade ago, the first initial condition (“large”) ensembles were
5 created (e.g., Deser et al. 2012a, 2012b) with a single model, followed by other models (Rodgers
6 et al. 2015) and large ensembles with up to 100 simulations (Maher et al. 2019). Currently there
7 are large ensembles from many other climate models (Deser et al. 2020), and the model
8 intercomparison protocol for the most recent generation of simulations encouraged large
9 ensembles of 10 members for all models (O’Neill et al. 2016).

10 Large ensembles have enabled us to estimate uncertainty from natural variability separately from
11 the structural uncertainty among climate models (Lehner et al. 2020). It has revealed dependence
12 of some aspects of natural variability, like precipitation, on climate state (Pendergrass et al.
13 2017). It has also enabled isolation of the response to different forcings, independent of natural
14 variability and assessment of the linearity of these responses (Deser et al. 2020) or lack thereof
15 (Pendergrass et al. 2019).

16 The size of a large ensemble needed to address questions related to the timing of when human-
17 induced climate change signals exceed the natural variability of the climate (Milinski et al. 2020)
18 and the general importance of large ensembles for risk assessment (Mankin et al. 2020), US
19 water resources (McKinnon and Deser 2021), air pollution and associated health impacts
20 (Garcia-Menendez et al. 2017; Saari et al. 2019) and ecosystem stressors (Frölicher et al. 2016)
21 are among emerging applications (see Deser et al. 2020 for other examples).

22 Large ensembles have also been used to assess whether ENSO events and their impacts on
23 precipitation and temperature over North America will change in the future (Maher et al. 2018;
24 Haszpra et al. 2020; Cai et al. 2021). They are also being used to assess how large-scale
25 atmospheric circulation patterns that affect US weather and climate may be altered by the effects
26 of climate change (O’Brien and Deser 2022).

27 Major Uncertainties and Research Gaps

28 To obtain decision-relevant information at the scale of impacts—regional to local—with
29 quantified uncertainty grounded in understanding of the natural variability, forcing, and
30 structural sources of uncertainty, much remains to be done. Identifying the forced pattern of
31 response on local scales and separating it from natural variability is a continuing challenge,
32 which has immediate implications for predictability, climate model evaluation, and the potential
33 to narrow uncertainty in climate projections. Another key challenge is the so-called signal-to-
34 noise paradox, which implies that models underestimate atmospheric predictability due to
35 incomplete representations of key atmospheric and oceanic processes (Scaife and Smith 2018).
36 Thus, as models improve, there may be the potential to deliver more skillful climate predictions.
37 Stakeholder and decision-maker input on what uncertainty is tolerable for specific applications,

and what this means for the size of large ensembles, is another outstanding topic. The role of natural variability for many impacts, including air quality, has yet to be fully addressed. Finally, the implications of potential changes in natural variability for decadal prediction and predictability are still open questions. For example, what is the timescale of predictability? How predictable is x variable on y timescale?

Description of Confidence and Likelihood

The *high confidence* in the statement about the importance of initial-condition large ensembles for quantifying the relative contributions of human-caused climate change and natural (or internal) climate variability on local and regional scales is based on decades of climate science research that shows that natural variability on these geographical scales is large and can obscure human influences on climate. Climate scientists agree that in addition to the standard CMIP approach of including simulations with multiple Earth system models, multiple simulations of past and future climate for each Earth system model are needed to separate models' structural differences from apparent differences arising from sampling of natural variability.

Key Message 3.6. Extreme Event Attribution

Description of Evidence Base

Since the landmark 2004 Nature paper of Stott et al. (2004) finding that the chances of the 2003 European heatwave doubled due to anthropogenic climate change, many different author teams have analyzed a wide variety of extreme weather events for the human influence, if any. This large literature has been developed using many different approaches that have been surveyed by the author team. Of particular interest are a series of special supplements to the annual State of the Climate report published since 2011 in the *Bulletin of the American Meteorological Society* (Herring et al. 2019, 2018, 2016, 2015, 2014; Peterson et al. 2013, 2012). Chapter authors have contributed to these reports and have published event attribution studies in the general literature.

Confidence in attributing the human influence, if any, on individual extreme weather event is increased when multiple independent author teams arrive at similar conclusions using different methods, observational datasets, and models, coupled with a thorough understanding of the physical processes of change. The copious amount of precipitation experienced in the greater Houston area during Hurricane Harvey provides a case in point, where three different teams concluded that anthropogenic climate change led to large attributable increases in storm total rainfall (Risser and Wehner 2017; van Oldenborgh et al. 2017; Wang et al. 2018). Confidence in this attribution has been further increased by the subsequent studies of other hurricanes, leading to similar conclusions (Patricola and Wehner 2018; Reed et al. 2020, 2021, 2022).

Confidence in extreme event attribution statement hinges on reliable, long-term observations (Knutson 2017). Fortunately, much of the CONUS is well observed since 1950 by the NOAA

Global Historical Climate Network weather station measurements of temperature and precipitation. In many locations, reliable records span an entire century (Menne et al. 2012). Attribution is an exercise in causal inference; climate change attribution studies borrow techniques from the well-established epidemiology literature. Typical Pearl causal inference experiments involve two groups, a controlled (or placebo) and a tested group (Pearl 2009). As there is only one planet, climate change attribution experiments can only be performed with numerical models. The limitations of climate models impose important caveats on any resulting attribution statements. The CMIP database of global climate models has been extensively used in attribution statements (Easterling et al. 2016; Stott et al. 2016). However, it is best suited for extreme events of larger spatial scales matching that of the CMIP models (e.g., heatwaves). More customized numerical experiments at higher resolution may be required for more localized extremes such as intense storms (including hurricanes) (Wehner et al. 2019). Granger causal inference has also been applied to long observational records to make attribution statements without using climate models (Ebert-Uphoff and Deng 2015; Granger 1969). While a weaker form of causal inference due to the possibility of hidden covariates in the underlying statistical models (i.e., statistical model construction may bias findings), Granger causal inference can add to our understanding of changes in extreme event frequency and magnitude.

Major Uncertainties and Research Gaps

Confidence in extreme attribution statement depends on both our understanding of the underlying physical mechanisms of change as well on the fitness of our statistical and climate models (Otto et al. 2020). This, of course, varies significantly depending on the nature of the extreme weather event. Attribution statements about the human influence on severe heatwaves and cold snaps are generally considered to be most confident (Seneviratne et al. 2021). Confidence in attribution statements about extreme precipitation vary greatly depending on storm type. Hurricane precipitation has been among the most studied, and it is clear that it has been increased by climate change. Atmospheric rivers and extratropical cyclones have received less attention, but it is expected that similar conclusions will be drawn as more studies are performed. Mesoscale convective systems (e.g., storms producing hail, tornadoes, and ice) are not so well-studied due to both modeling and observational limitations of these specific local-scale events.

Changes in extreme wind events, such as produced by hurricanes, derechos or Santa Ana-type events are also poorly understood due to model limitations.

Extreme weather changes attributable to local thermodynamic processes are better understood than those due to changes in large-scale meteorological patterns due to uncertainty in changes in circulation patterns. Thus, attributable changes in meteorological drought (defined by rainfall deficits) caused by changing rainfall patterns from circulation are less well understood, especially for CONUS, than are attributable changes in agricultural and ecological drought

(defined by increases soil moisture deficit caused by warmer temperatures) (Wehner et al. 2017).

Some events are so extreme that our statistical and climate models may not be fit for the purpose of quantifying the human influence, even if our understanding is such that we are confident that there is one. The 2021 heatwave in the Pacific Northwest is a good example. Temperatures experienced during this very rare, compound extreme event are outside of the bounds of the fitted generalized extreme value (GEV) statistical distributions typically used to ascertain changes in event frequency and magnitude. Also, it is unclear whether the standard ensemble of CMIP models can produce the specific large-scale meteorological patterns responsible for these record-breaking temperatures. For these very rare events, the recent development of large ensembles of climate models can increase our confidence in quantitative attribution statements in some instances (Deser et al. 2020).

Description of Confidence and Likelihood

The methods behind event attribution statements have improved dramatically since NCA4 and will continue to do so. Application of advanced statistical methods, together with larger ensembles of higher resolution models has led to *high confidence* in understanding how humans have influenced the frequency and magnitude of a wide variety of individual extreme weather events.

Key Message 3.7. Observations for Improving Process Understanding and Modeling

Description of Evidence Base

From temperature and precipitation observations that began in the 1800s, through the earliest observations of CO₂ concentration taken on Mauna Loa from the late 1950s, and into the satellite era, observations of the Earth system have been essential for us to constrain climate models and our understanding of the climate system. The components of the climate system are strongly interconnected, with physical processes constraining meteorological and climatological fields. New observing systems enable either more accurate or detailed examination of known variables, or the examination of new variables.

Major Uncertainties and Research Gaps

Unfortunately, not all quantities of relevance in the Earth system can be easily observed. Although recent satellite missions such as GRACE (Richey et al. 2015) have been able to use gravitational measurements to constrain subsurface moisture, much of the subsurface remains poorly understood. Ongoing work has also suggested that deep ocean heat content may have been underestimated (Cheng et al. 2017), a consequence of insufficient measurements of the deep ocean. Further, in situ measurements are generally more available within developed

countries and in more easily accessed regions, resulting in significant observational gaps in the Southern hemisphere (e.g., Guo et al. 2009) and at high elevation (Hock et al. 2019; Thornton et al. 2022).

Description of Confidence and Likelihood

There is *high confidence* that observing systems have reduced uncertainty in climate projections and improved our understanding of the climate system. In situ and remote observing systems have provided and continue to provide a growing wealth of data on the global Earth system. Scientists leverage this observational data to develop and constrain models that reflect the physical processes relevant for the Earth system. There are far too many examples of these observations leading to new scientific discovery to highlight here. Since the NCA4, one of most recognized examples has come from tighter constraints on climate sensitivity obtained from observations, paleoclimate records, and model response (Sherwood et al. 2020). Hence there is also *high confidence* that new techniques that synthesize information from models and observation data have advanced understanding of the climate system.

Key Message 3.8. Water Cycle Changes

Description of Evidence Base

The supporting text summarizes the current state of understanding and includes key citations to peer-reviewed literature describing the evidence on which the Key Message is based.

Major Uncertainties and Research Gaps

One uncertainty is the role of vegetation in modulating changes in evapotranspiration, which can in turn influence other factors including soil moisture, streamflow, and wildfire.

A key gap for understanding the hydrologic cycle and how it can change is the enormous range of scales in space and time on which relevant processes operate, from the scale of nanometers (cloud condensation nuclei), to the scale of cloud systems and watersheds (1 km to 1,000s of km), to the whole globe (evaporation and precipitation constitute a large fraction of energy flow between the surface and atmosphere). No observing system can capture, and no numerical model can represent, all of these processes at once, which are key challenges for understanding and projecting the water cycle and its change. Continuing to increase the range of scales that can be captured by consistent, continuous observing systems and represented within a single model is one promising path toward decreasing some of the uncertainty in the future water cycle.

Description of Confidence and Likelihood

The processes relevant to the water cycle are sorted according to confidence level which integrates the current view of how likely they are to change and the depth of our understanding of this change. *High confidence* indicates that the change in the process is supported by multiple

types of observations, model simulations, and theory, and extensively documentation in the peer-reviewed literature. *Low confidence* indicates processes that are not well observed, poorly represented in models, lacking in theory, and/or an emerging research focus. Details for each process are reflected in the text.

Of note is the potentially counterintuitive role of natural variability for many aspects of the water cycle (especially for changes at the regional scale): natural variability is known (*high confidence*, from observations, theory, and simulations) to be large for many aspects of the water cycle, and this can result in a low ceiling to the likelihood that can be placed on any specific realization of the future or past water cycle, even in situations where confidence in understanding is high. For this reason, it is particularly important for the water cycle to focus on probability of what could happen in the future and the probability that observed changes that have already occurred are due to forced changes (as opposed to natural variability), rather than focusing on specific, deterministic trajectories of what has already happened or will happen in the future.

Key Message 3.9. Changes in the Carbon and Biogeochemical Cycles

Description of Evidence Base

Observations show that about half of annually emitted CO₂ is absorbed by the terrestrial biosphere and oceans (Friedlingstein et al. 2020). The observational record of atmospheric CO₂ growth and estimates of fossil fuel emissions based on economic fuel statistics are used to estimate the residual total uptake of carbon by the terrestrial ecosystem and the ocean. Determining the amount of uptake for land and oceans is more complicated and uncertain. For the oceans, upscaled global measurements of the partial pressure of CO₂ (pCO₂) in seawater and total carbon in organic and inorganic compounds dissolved in interior ocean waters are used to estimate current and cumulative carbon sinks (e.g., Takahashi et al. 2009; Rödenbeck et al. 2015). On land, direct measurements of atmosphere–land biosphere fluxes can be used to understand carbon sources and sinks and their variability on daily and interannual timescales (Baldocchi et al. 2005).

Major Uncertainties

Scaling these estimates up to global and regional scales is difficult because carbon fluxes are spatially heterogeneous, and this is especially true for terrestrial carbon fluxes. Observations used to estimate carbon fluxes are sparsely distributed, and data records are often too short to be used to characterize interannual variability and trends. Models of ocean circulation and biogeochemistry and detailed models of plant growth and dynamics can be used to upscale carbon fluxes using observations for guidance, but there is significant uncertainty in many processes, such as the effects of nutrient limitation and responses to climate changes. Machine learning approaches have also been used to upscale flux observations (e.g. Jung et al. 2020). Inverse modeling combines information from atmospheric observations, atmospheric transport models, and best-available estimates of carbon fluxes from land and ocean via models to produce

carbon flux estimates; however, these modeling systems are also limited by sparse data. Major regions that are important for understanding the global carbon budget, such as the tropics and Siberia, do not have adequate observational coverage and this lack makes accurate estimates of land and ocean fluxes difficult to achieve.

All of the above-mentioned issues, and the large uncertainty associated with future emissions, make predicting the future evolution of the carbon cycle difficult. Uncertainties in future climate drivers such as temperature, precipitation, and cloudiness result in uncertainty in how land and ocean biogeochemistry will evolve in the future. Furthermore, the difficulties in modeling nutrient availability and limitation, disturbances such as fires, insect and disease outbreaks, severe weather, and even human land-use change are all complications that affect predictions of how the carbon cycle and climate change will interact. The mobilization to the atmosphere of CO₂ and CH₄ from enhanced decomposition of the huge reserves of carbon in Arctic soils represents a potentially important positive carbon cycle–climate feedback, but it is particularly difficult to model due to difficult-to-quantify process like cryoturbation and local erosion and thermokarst processes (Natali et al. 2021). Current carbon cycle models that are coupled to climate models disagree widely on the future response of carbon exchanges between the oceans land biosphere and atmosphere to continued fossil fuel emissions. The range of responses has not appreciably changed since the previous model intercomparison (CMIP5, Arora et al. 2020).

Description of Confidence and Likelihood

Confidence is *high* that roughly half of fossil fuel emissions are taken up by global oceans and the terrestrial biosphere. This conclusion is based on accurate global atmospheric observations and the global fossil fuel consumption is well known. On the other hand, projections of how the global carbon cycle will evolve in response to future climate change, and how the changing climate will in turn affect climate are still uncertain. Continued research, expanded observations, and more accurate models are needed to reduce the uncertainty range.

Key Message 3.10. Changes in Ocean and Cryosphere and Sea Level Rise

Description of Evidence Base

Over the course of the 20th century, sea level rise occurring on global scales estimated from reconstruction created from tide-gauge records has been explained by the individual processes contributing to it (Frederikse et al. 2020). These process contributions were estimated from a combination of direct observations and observation-driven reconstructions. Using modern observation systems, global sea level rise from satellite altimetry over the past 15 years has been explained using the in situ measurements of the Argo profiling floats and the observations of water-mass change from the GRACE and GRACE-FO satellites (Wouters et al. 2018), demonstrating closure of the global sea level budget. As seen in both tide-gauge and satellite records, the rate of GMSL rise has been increasing, driven by accelerating contributions from the underlying processes (Nerem et al. 2018; Dangendorf et al. 2019; Frederikse et al. 2020).

At the regional level, similar studies have assessed the rates of sea level rise and performed similar budget studies as those conducted on global scales. Sea level rise is not uniform across the globe; rather, it manifests as relative sea level rise that also responds to several key factors important at regional and local scales. The combination of models, reconstructions and observations allow for accounting of all the relevant processes, and an understanding of the drivers of total sea level rise has been demonstrated on regional scales across a range of different timescales in several studies (e.g., Frederikse et al. 2017; Rietbroek et al. 2016; Walker et al. 2021; Harvey et al. 2021). The current relative sea level observation network measures the dominant processes contributing to regional sea level and this has supported more dedicated, process-level studies on sea level rise.

Major Uncertainties and Research Gaps

Many of the components of the modern sea level observation network are limited in coastal regions, particularly space-based platforms. The US coastlines have better coverage from tide gauges than other parts of the world, although large gaps between tide gauges are still present. This is also true of measurements of coastal subsidence that generally originate from point-measurements from GPS, although satellite-based interferometric synthetic aperture radar (InSAR) provides a possible solution (e.g., Shirzaei et al. 2021). The connection between open ocean sea level change and the sea level change experienced at the coast is still an active research area.

As a result of observations and improved modeling efforts, there is increased consensus regarding the behavior of many of the ice sheet processes. However, the future response of the ice sheets as the climate continues to warm and some of the associated processes are still uncertain. In particular, two possible processes, known as the marine ice cliff instability (Deconto and Pollard 2016; Deconto et al. 2021) and the marine ice sheet instability (Hoffman et al. 2019; Robel et al. 2019; Morlighem et al. 2020), have been hypothesized that could lead to rapid ice sheet loss over the course of several decades. The physical processes that would result in these instabilities and how they would progress once triggered remain uncertain.

Description of Confidence and Likelihood

As a result of the continuity and enhancement of the sea level observing network and the advances made in both historical reconstructions and modeling, there is *high confidence* that the assessment of process-based contributions to sea level rise on a regional level has improved. Several studies demonstrate the direct link between advances in observations, models, and reconstructions to this improved understanding. The understanding of the near-coast processes that contribute to sea level change is still evolving in some locations, particularly in areas without an available in situ measurement of sea level. As a result, there is *medium confidence* in the behavior of processes that cause sea level change at the coast, in general. Disagreement in the behavior of some of the possible physical processes in the cryosphere, particularly with regards

to the Antarctic ice sheet, leads to *low confidence* in the potential for rapid ice mass loss that contributes to rapid sea level rise along the US coastlines.

Key Message 3.11. Atmospheric Circulation Changes

Description of Evidence Base

Many aspects of atmospheric circulation changes have been studied using observations (global reanalysis) and model simulations. Important large-scale circulation features that influence US regional climate include the jet stream, storm tracks, Aleutian low, North Pacific and North Atlantic subtropical high, North American monsoon circulation, and others, which are strongly influenced by the overturning Hadley circulation in the tropics. In turn, large-scale circulation such as the North Atlantic subtropical high influences mesoscale circulation features such as the Great Plains low-level jet that affects precipitation in the central and midwestern US. Hence understanding how the Hadley circulation changes with warming is important for understanding changes in large-scale and mesoscale circulations affecting US regional climate. Staten et al. (2018) and Grise et al. (2019) synthesized previous studies documenting the poleward shift in the subsiding branches of the Hadley circulation since 1979. Both studies found that methodological differences in how the Hadley circulation is calculated can partly explain the discrepancy between the rate of tropical expansion derived from global reanalyses and model historical simulations found in previous studies. However, both studies also highlighted the challenge in detecting changes in the tropical expansion and attributing them to anthropogenic warming because of the large natural variability, particularly for the poleward expansion in the northern hemisphere that is more relevant to large-scale circulations affecting North America.

Besides the tropical expansion, many studies analyzed model simulations and projections of changes in large-scale circulation such as the jet stream (Neelin et al. 2013; Shaw and Voigt 2015; Dong et al. 2021a; Zhou et al. 2022b), storm tracks (Chang et al. 2012), extratropical cyclones (Colle et al. 2015; Zarzycki 2018), and North Atlantic subtropical high (Li et al. 2012; Song et al. 2018a). Many of these studies used multimodel and large ensemble simulations to first determine if a robust signal of change is found, and if so, the mechanisms for how warming may influence the circulation features; the impacts of the circulation changes to precipitation are also often investigated. Model experiments allowing isolation of the direct radiative effect of CO₂, which is a fast process, versus the effect of sea surface temperature warming, which is a slower process, have also contributed to improving understanding of how increasing greenhouse gases affect atmospheric circulation.

Major Uncertainties and Research Gaps

While advances have been made in reconciling the previously reported differences in tropical expansion rates in observations and model simulations, uncertainties remain, especially in future projections of tropical expansion in the northern hemisphere because of the large natural variability and the relatively small poleward expansion in response to increasing greenhouse

gases (Grise et al. 2019). Some studies also highlighted several important sources of uncertainty in projecting midlatitude atmospheric circulation changes related to model biases (e.g., Dong et al. 2021b), a tug-of-war between opposing mechanisms (e.g., Shaw and Voigt 2015), and natural variability (e.g., Deser et al. 2020; Dong et al. 2021a).

As discussed in KM 3.11, large-scale circulation changes are influenced by meridional and vertical temperature gradients so Arctic amplification (the enhancement of near-surface air temperature change over the Arctic relative to lower latitudes), besides changes in the tropical Hadley circulation, may also influence mid-latitude atmospheric circulations such as blocking, with potential implications for cold extremes. However, significant challenges remain in connecting Arctic amplification to midlatitude circulation changes due to the complex nonlinear dynamics of jet stream (Cohen et al. 2020; Doblas-Reyes et al. 2021).

Description of Confidence and Likelihood

Since NCA5, important advances have been made in providing multimodel simulations, large ensemble simulations from multiple models, and other types of model experiments to evaluate the fast and slow response to increasing greenhouse gases. These simulations, in combination with observations, have allowed more analysis of various factors and mechanisms contributing to past and future changes in atmospheric circulation and uncertainty in model projections. Considering the complexity of midlatitude nonlinear dynamics and our incomplete understanding, model uncertainty, and natural variability, we only have *medium confidence* in how increasing greenhouse gases affect tropical expansion and hence atmospheric circulation.

Key Message 3.12. Changes in Extreme Events

Description of Evidence Basis

The science of extreme event attribution has advanced significantly over the last decade (Stott et al. 2016; van Oldenborgh et al. 2021), increasing our ability to detect observed changes in extremes and attribute changes to natural and anthropogenic effects. Typically, attribution compares model simulations of recent and past climates that include or exclude estimated aspects of anthropogenic forcing (e.g., greenhouse gases, atmospheric aerosols, land surface, and vegetation conditions) to determine how climate change affects the frequency, duration, and/or intensity of extreme events. There is no unified theory of attributing weather and climate extremes, meaning that changes in one extreme (e.g., drought) cannot be necessarily generalized to other extremes (e.g., floods). This is because different extremes are governed by different physical processes that may respond in distinct ways to anthropogenic effects.

Major Uncertainties and Research Gaps

Land surface and vegetation processes have substantial impacts on climate extremes through the modulation of energy fluxes between the surface and atmosphere and surface water partitioning (Seneviratne et al. 2010). For example, dry surface conditions (e.g., a drought) and urbanization

can both amplify heat extremes (Miralles et al. 2019; Zhou et al. 2022c), while wetter soils can increase the risk of precipitation events causing large floods (Merz et al. 2021; Schröter et al. 2015). However, few long-term data on these processes are available at large scales (Miralles et al. 2019), and their representation in climate models is often highly simplified (Fisher and Koven 2020). Further, despite the fact that many extremes are strongly tied to atmospheric circulation anomalies (e.g., atmospheric ridge events), changes in these dynamics remain highly uncertain. While changes in sea ice and meridional temperature gradients may be linked to increases in the frequency and persistence of midlatitude circulation patterns associated with extreme events (e.g., Coumou et al. 2018), studies suggest that these changes have not yet emerged from background natural variability (Osman et al. 2021). Finally, climate change may be moving us into an era of large or unprecedented extremes that fall far outside the range of historical variability, particularly regarding temperature (e.g., Overland 2021). In such cases, many statistical approaches may be insufficient, and make it difficult, with any confidence, to conduct detection and attribution analyses (Philip et al. 2021).

Description and Confidence Likelihood

Anthropogenic forcing has increased the frequency, duration, and intensity of extreme heat across most land areas (*high confidence*; Perkins-Kirkpatrick and Lewis 2020; IPCC 2021), with some evidence that extreme cold events have also declined (*medium confidence*; Stott et al. 2016). These changes are driven by mean shifts in the temperature distributions towards warmer conditions that are significant and robust across most of the world (Baldwin et al. 2019). Heavy precipitation events have increased in some regions (*high confidence*; IPCC 2021) because of the strong dependence of the water holding capacity of the atmosphere on temperatures (e.g., Kunkel et al. 2013). Coastal flood risk has, and is projected to, increase because of sea level rise (*high confidence*, e.g., Vousdoukas et al. 2018). Notably, while the most extreme river floods are expected to increase in severity because of increases in heavy precipitation (*high confidence*), more general trends are mixed because flood risk also depends on policies and land surface processes (Douville et al. 2021). Soil moisture droughts are also increasing in frequency and severity in many regions (*medium to high confidence*; IPCC 2021) through the direct effects of warming on snow, evapotranspiration, and plant water use (Mankin et al. 2019; Siirila-Woodburn et al. 2021; Wang et al. 2022). There is also *high confidence* that the intensity and frequency of precipitation droughts are increasing in Mediterranean-climate regions (Gudmundsson and Seneviratne 2016; Kelley et al. 2015; Otto et al. 2018; Seager et al. 2019). Climate change increases fuel flammability through higher temperatures and lower humidity and has increased the area burned by wildfires in western US (*high confidence*, Abatzoglou and Williams 2016; Williams et al. 2019) and Australia (Abram et al. 2021). Despite these climate change-driven regional increases, however, global burn area has declined in recent years as a consequence of agricultural expansion and intensification, especially in savanna and grassland ecosystems (Andela et al. 2017).

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4. Water

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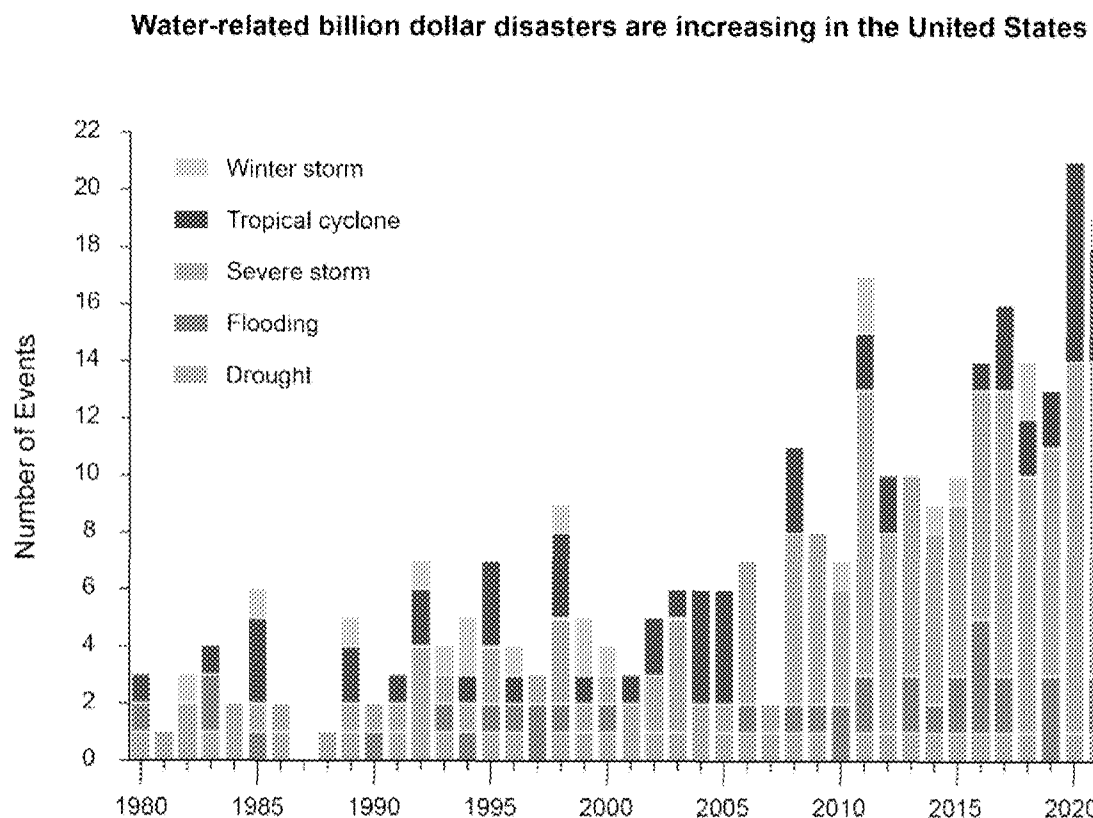
1	Chapter Contents	
2	Introduction	3
3	Key Message 4.1. Profound Changes to the Water Cycle	5
4	Box 4.1. Washington–California 2015 Snow Drought	13
5	Key Message 4.2. Rising Risks, Disproportionate Impacts.....	15
6	Box 4.2 Climate Change, Urban Flooding, and Inequality	18
7	Key Message 4.3. Slow Progress Toward Adaptation	21
8	Box 4.3 International Cooperation in the Great Lakes	21
9	Traceable Accounts	26
10	References.....	31
11		

1 Introduction

2 Climate change is intensifying rainfall and floods, deepening droughts, and shifting typical
3 weather patterns across the globe (IPCC 2021). Rising sea levels, reduced snowpacks, shrinking
4 rivers, and declining groundwater threaten cities and rural communities and endanger forest,
5 riverine, and other ecosystems across the United States.

6 Combined with greater exposure and vulnerability, climate change is increasing the frequency of
7 water-related disasters in the US (Figure 4.1).

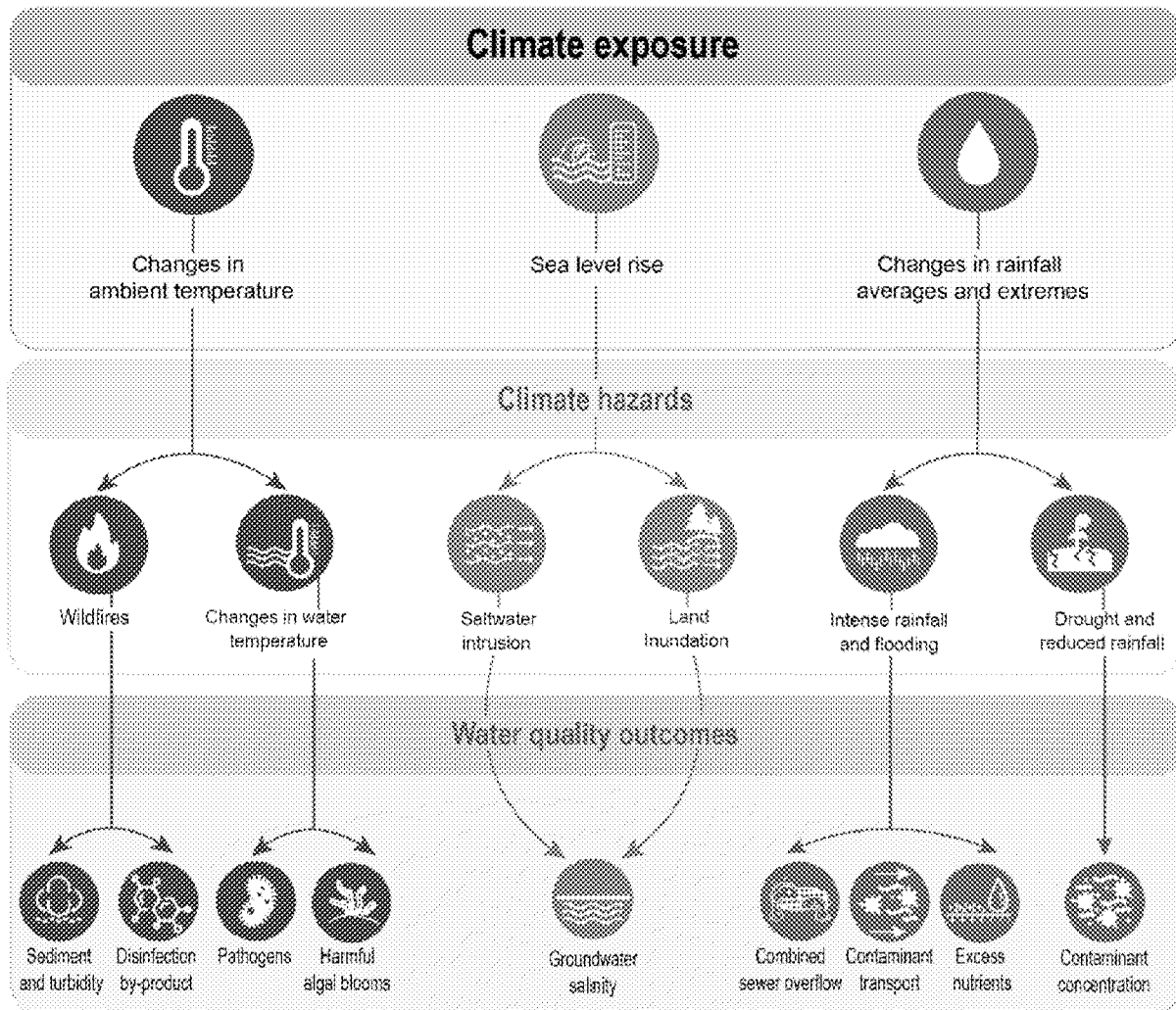
8 **Figure 4.1. Water-Related Disasters**



9
10 CAPTION: The number of billion-dollar water-related disasters across the US during 1980–2021 rose due
11 to increases in exposure, vulnerability, and frequency of extremes. Adapted from (NOAA NCEI 2022;
12 Smith 2020).

13 Water security depends on adequate supplies of clean water (KM 15.2). However, climate
14 change is expected to degrade water quality for people and ecosystems (Figure 4.2; Nijhawan
15 and Howard 2022; CDC 2022; Delpla et al. 2009).

1 Figure 4.2. Climate Change Impacts to Water Quality



2
3 CAPTION: Climate change threatens the quality of freshwater supplies across the United States.

4 Saltwater intrusion is an imminent threat to coastal and island communities dependent on groundwater
5 for drinking water (KM 30.1); agricultural areas face risks to their water supplies when nutrients are
6 mobilized by flooding (KM 25.2); many areas are at risk of exposure to harmful algal blooms (e.g., KM
7 22.2); and treatment plants downstream of forested areas are challenged by wildfire sediments and
8 debris in their source waters (KM 6.1). Adapted from Nijhawan and Howard (2022).

9 Climate change is forcing a reexamination of our concepts of rare events. Extreme precipitation
10 incidents are more intense and more frequent (KM 2.2), extended droughts in the West appear to
11 be due in part to long-term aridification rather than episodic drying (Hoylman et al. 2022;
12 Overpeck and Udall 2020), and compound hazards are expected more often as the events that
13 combine to create them become more frequent (Focus on Compound and Complex Events).

The US is slowly adapting to these changes. Some water providers are exploring ways to integrate change into planning, and municipalities, states, tribes, and border nations are working cooperatively to seek solutions to water shortages and flooding. But barriers arise from legal and regulatory institutions that have been in place for decades or even centuries, locking in practices that hinder adaptation. The Nation's aging water infrastructure, designed under regulations and standards appropriate to an unchanging climate, is deteriorating and threatening public health (ASCE 2020; Lall et al. 2018). There is growing recognition that many overburdened populations, including Indigenous and tribal communities, are suffering disproportionate impacts—but also that these groups possess knowledge that can support climate solutions.

We are making progress on some fronts. The tools and data needed to support water resources planning and management are becoming more sophisticated and widely available, although gaps remain, particularly in local data availability. There has been enormous growth in the availability of science-based climate information for water providers and natural resource managers, demonstrating increasing awareness and demand for solutions. These and similar efforts are the first steps toward building resilient human and natural systems in the face of the many risks posed by the changing water cycle.

Key Message 4.1. Profound Changes to the Water Cycle

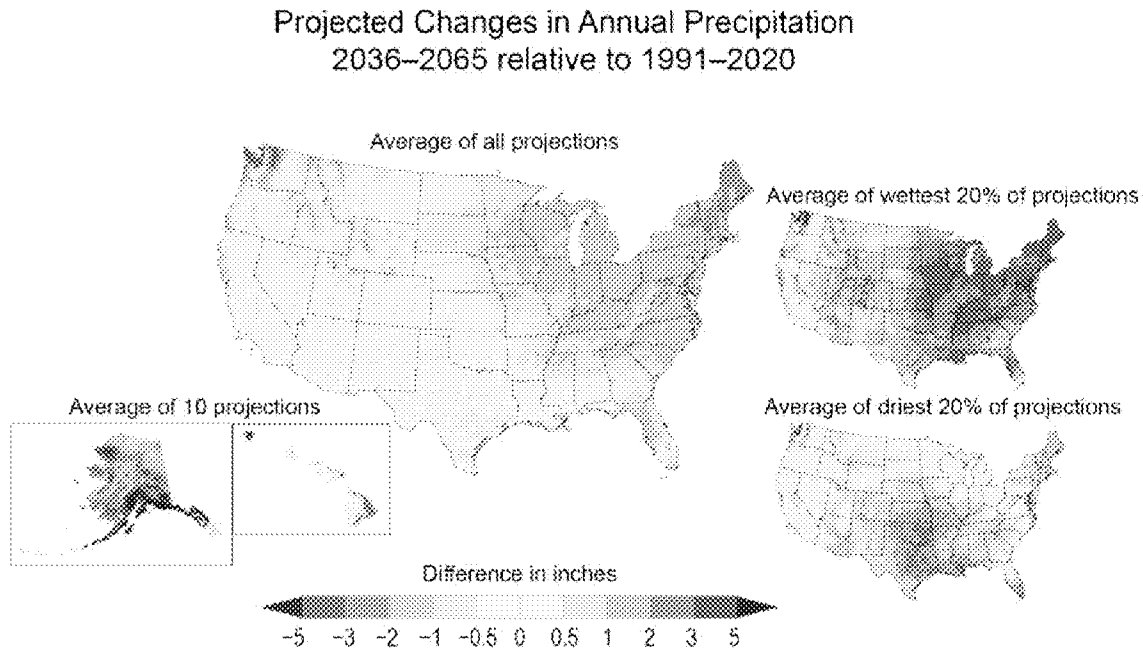
Climate change has caused profound shifts in the water cycle, creating risks for both people and nature (*high confidence*). Many regions of the United States are expected to see more precipitation and heavier rainfall (*likely, medium confidence*), resulting in increasing flood damage. However, warming will also increase the rates at which water is transferred to the atmosphere from open water, soil, and plants, increasing aridity and drought risk and threatening surface and groundwater supplies (*very likely, high confidence*). In many locations, snow cover is decreasing and melting earlier (*very likely, high confidence*), posing risks to agriculture and municipal water supplies, and natural systems (*high confidence*).

Water cycles through and is stored in interrelated components of the hydrologic system. Changes to these components are occurring across the Nation. This chapter touches on these changes, but important regional differences exist and are described in the regional chapters.

Precipitation Changes

Climate change has already shifted precipitation patterns across the country, including increased variability and elevated likelihood of extreme rainfall events (KM 3.8). These trends exhibit substantial regional and seasonal variations (KM 2.1), such that some areas will receive too much rain and some will receive too little. Projected changes in annual precipitation also exhibit large regional differences (Figure 4.3).

1 **Figure 4.3. Projected Precipitation Changes**

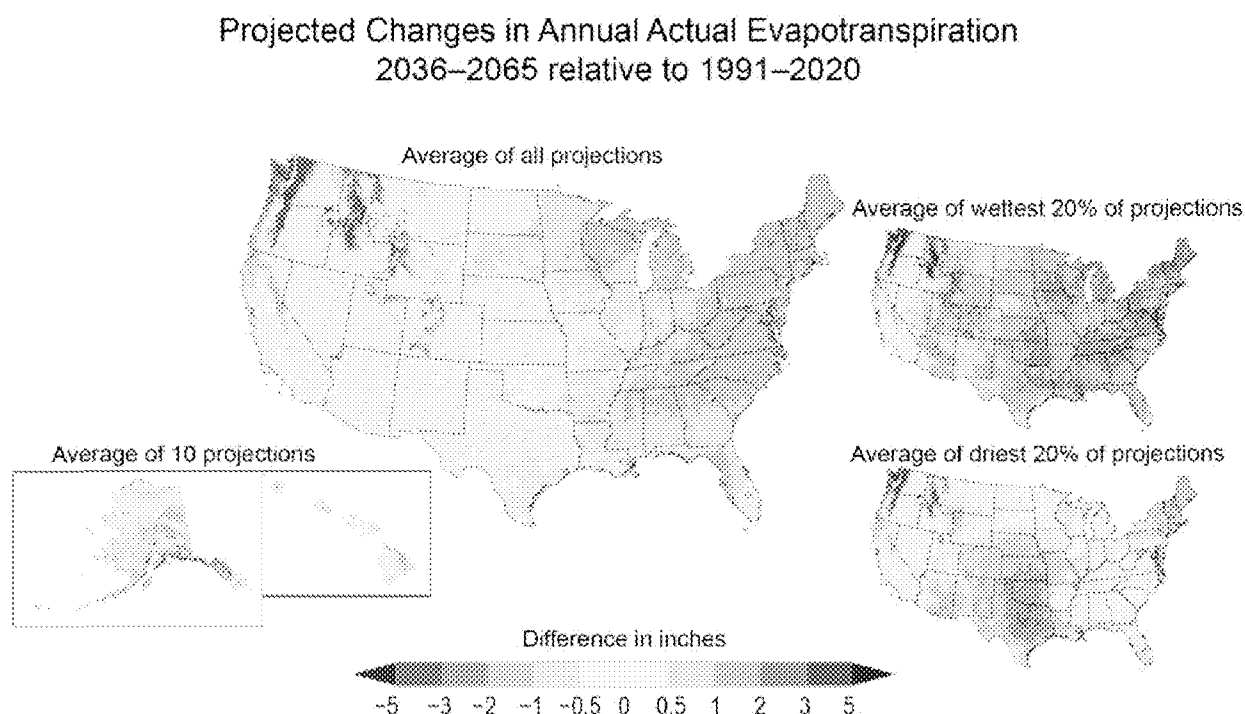


2
3 **CAPTION:** Under the intermediate (RCP4.5) emissions scenario, annual precipitation is projected to
4 increase for much of the continental US and to decrease in the US Southwest, Hawai'i, and the
5 Caribbean (not shown; Ch. 23). The wettest and driest 20% of projections show the range of CMIP5
6 outcomes. Note that this figure shows projected changes in inches. In the Southwest, a half-inch
7 decrease in annual precipitation has more influence on the region's hydrology than does a half-inch
8 increase the Northeast. Figure 2.9 provides the same information in terms of percent changes. Source:
9 University of Colorado Boulder.

10 **Evapotranspiration Changes**

11 Evapotranspiration (ET) is water lost to the atmosphere through evaporation from soil and
12 surface water and through transpiration by plants. Changes to temperature, precipitation, and
13 other climate variables combine to drive ET up or down (KM 3.8). Actual evapotranspiration
14 (AET) is ET limited by water availability. In the continental United States, AET has trended
15 lower in the Southwest as water availability has declined, while the East and North show the
16 opposite (Tercek et al. 2021). These trends are projected to continue with climate change (Figure
17 4.4).

1 **Figure 4.4. Projected Evapotranspiration Changes**

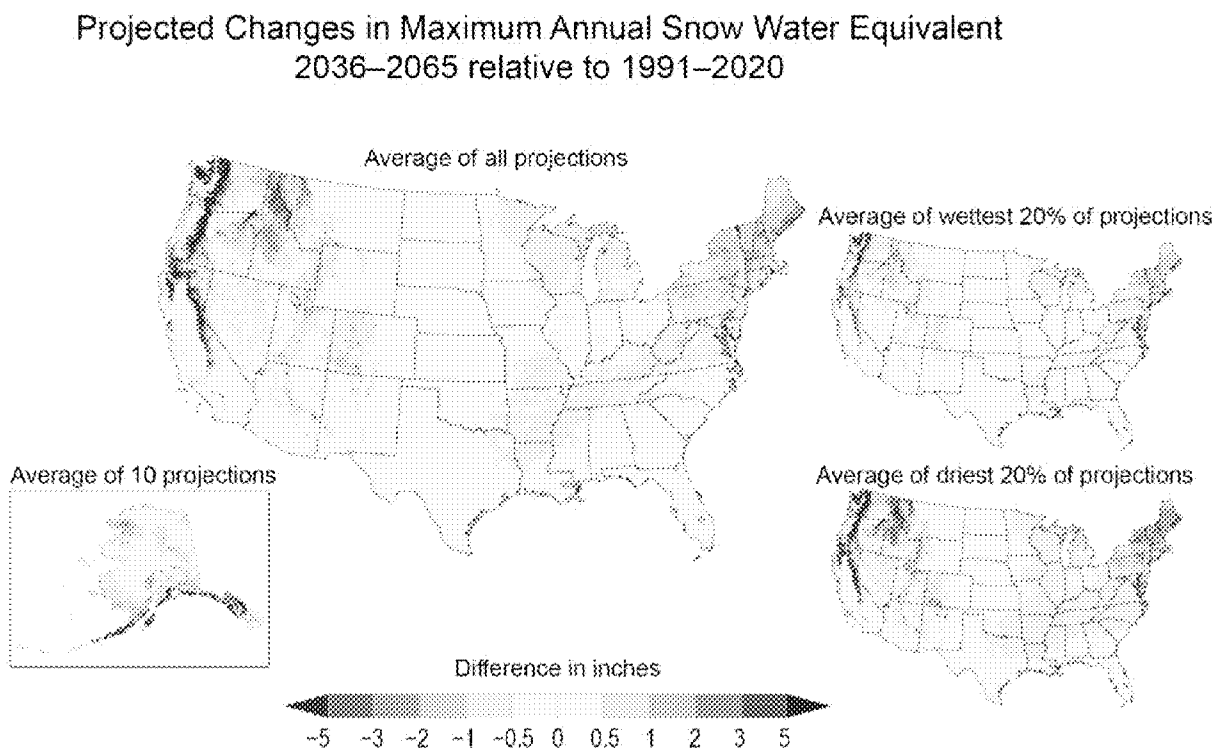


CAPTION: Under the intermediate emissions scenario (RCP 4.5), despite increasing temperatures, projected actual evapotranspiration (AET) is expected to decrease in regions with decreasing or unchanging precipitation, such as the US Southwest, Texas, and the Caribbean (not shown; Ch. 23). Wetter regions, including the Northwest, Alaska, and the eastern half of the continental US, are projected to have higher AET. Source: University of Colorado Boulder.

8 **Snow and Glacier Changes**

Snow is a natural reservoir, storing cold-weather precipitation and later releasing water through snowmelt. With higher temperatures, the fraction of precipitation falling as rain instead of snow will increase (Hale et al. 2022; Hamlet et al. 2005; Mote et al. 2005). Warming will also cause earlier snowmelt (Hale et al. 2022; Musselman et al. 2021), altered rates of snowmelt and evaporation directly from the snow (Musselman et al. 2017; Barnhart et al. 2016), and longer snow-free periods (Breckheimer et al. 2020; Myneni et al. 1997). Most historical snow-observation records show a trend toward earlier peak snowpack, smaller volumes, and decreasing snow-season duration (Figure A4.7), particularly for warmer maritime and lower-elevation regions (Siirila-Woodburn et al. 2021; Vano et al. 2015; Nolin and Daly 2006). In areas of the West where snow is the dominant source of runoff (Rauscher et al. 2008), total seasonal snow-water volume is projected to decrease by more than 24% by 2050 under intermediate (RCP4.5; Figure 4.5) and higher scenarios, with persistent low-snow conditions emerging within the next 60 years (Siirila-Woodburn et al. 2021). Reductions in snow cover are also accelerating the retreat of glaciers (Moore et al. 2009) that are critical for summer streamflow in Alaska (Mizukami et al. 2022; KM 29.6) and the Pacific Northwest (Ch. 27).

1 **Figure 4.5. Projected Snow-Water Content Changes**



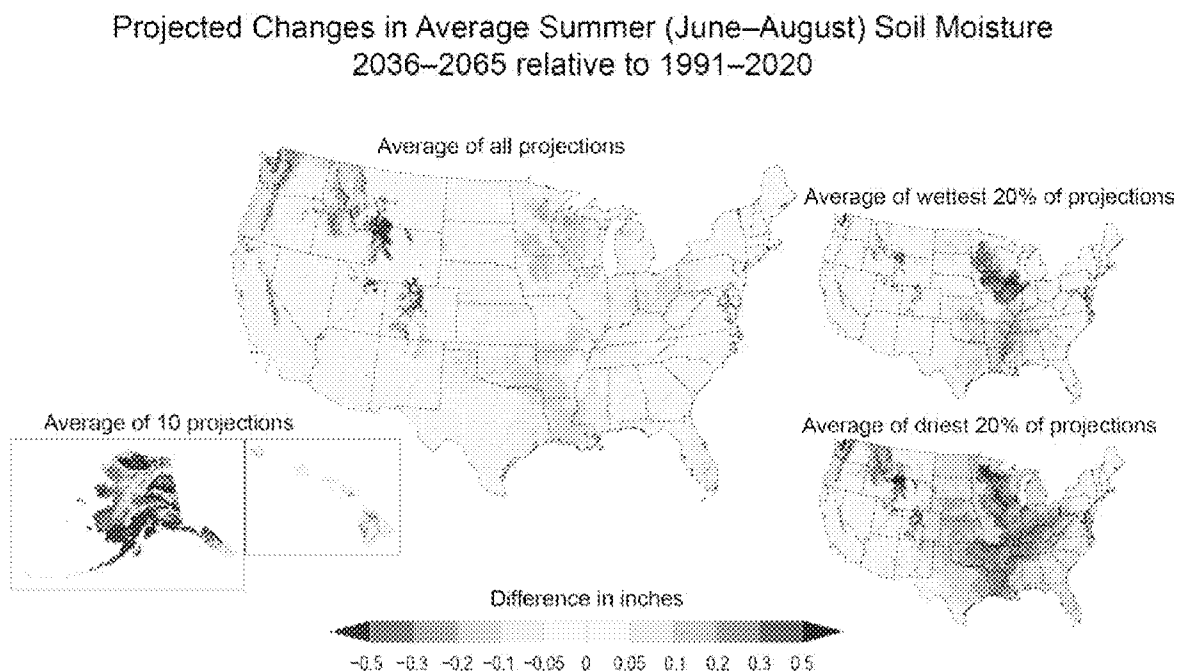
2
3 **CAPTION:** Under the intermediate emissions scenario (RCP 4.5), peak snowpack water content, key to
4 regional water supplies, is projected to continue to decline in all parts of the country that typically
5 receive snowfall, with the largest declines expected in the US Northwest and Alaska. Hawaii not included
6 because snow does not occur except for on the highest mountain peaks. Source: University of Colorado
7 Boulder, NOAA NCEI, and CISESS NC.

8 **Soil Moisture Changes**

9 Soil moisture is water stored in the soil, usually very close to the surface. It is a key component
10 of the water cycle, supporting agriculture and ecosystem productivity, modifying streamflow by
11 absorbing precipitation and snowmelt, and modulating climate (Zhou et al. 2021; Yang et al.
12 2018). A scarcity of soil moisture observations (Ford and Quiring 2019) has led to disagreement
13 regarding overall amounts, seasonality, and the direction of changes; however, there is consensus
14 that soils are becoming drier in the Southwest (Deng et al. 2020; Gu et al. 2019; Cheng et al.
15 2017).

16 Projections suggest that soil moisture will decrease in most of the country (Figure 4.6; Marvel et
17 al. 2021), although it may increase in the northern US and Alaska (Berg et al. 2017). The
18 Northwest and East are projected to experience seasonal changes in soil moisture, with wetter
19 soils in winter and drier soils in summer (Marvel et al. 2021).

1 **Figure 4.6. Projected Summer Soil Moisture Changes**



2
3 **CAPTION:** Under the intermediate (RCP 4.5) emissions scenario, summer soil moisture, essential for
4 water supply, agriculture, and ecosystems, is projected to decrease during the summer months (June,
5 July, and August) for most of the country. Exceptions include portions of the upper Midwest and Alaska.
6 Data not available for the US Caribbean. Source: University of Colorado Boulder, NOAA NCEI, and CISESS
7 NC.

8 **Groundwater Changes**

9 Groundwater is water stored below the land surface that has accumulated from precipitation; it
10 can be very close to the surface or extend hundreds of feet deep. It is a crucial water supply for
11 human systems and can moderate changes in temperature and precipitation (Condon et al. 2020;
12 Maxwell and Kollet 2008). The hydrologic connections between surface and groundwater make
13 surface water systems vulnerable to declining groundwater levels (Jasechko et al. 2021; Condon
14 and Maxwell 2019).

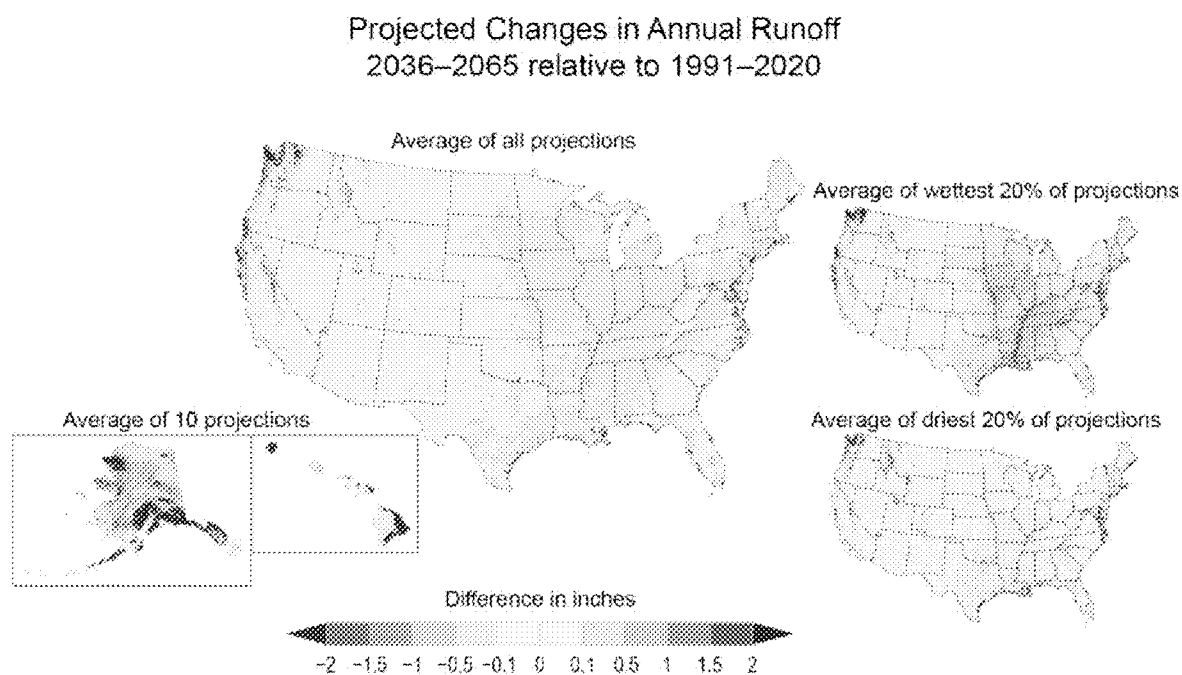
15 Higher temperatures are projected to decrease natural groundwater recharge and increase
16 irrigation water requirements across much of the West (Niraula et al. 2017; Meixner et al. 2016).
17 Increased irrigation demand can in turn lead to increased groundwater pumping in areas where
18 groundwater is the primary water supply or where surface water supplies are limited (Alam et al.
19 2019; Wada and Bierkens 2014; Taylor 2014). Groundwater levels have been declining in major
20 aquifers due to overpumping and decreased recharge; increased pumping could accelerate long-
21 term storage losses (Alam et al. 2019; Scanlon et al. 2012; Hanson et al. 2012).

Groundwater quality is also threatened by climate change. Warmer soil and groundwater temperatures can lead to decreased oxygen saturation, lower pH, and enhanced mineral weathering, all of which reduce water quality (Riedel 2019), and coastal and island aquifers are at risk of seawater intrusion rendering groundwater unpotable (KMs 9.2 and 23.3).

Runoff Changes

Changes to the water cycle components discussed above combine with other factors to affect runoff (surface water flow). For example, snowpack changes impact the seasonality of runoff in snowmelt-dominated areas (Dudley et al. 2017), while summer soil moisture affects the amount of precipitation and snowmelt that becomes runoff (Das et al. 2011). Increases in heavy precipitation events are projected to increase annual runoff over much of the US (Chegwidden et al. 2020; Naz et al. 2018; Figure 4.7).

Figure 4.7. Projected Runoff Changes



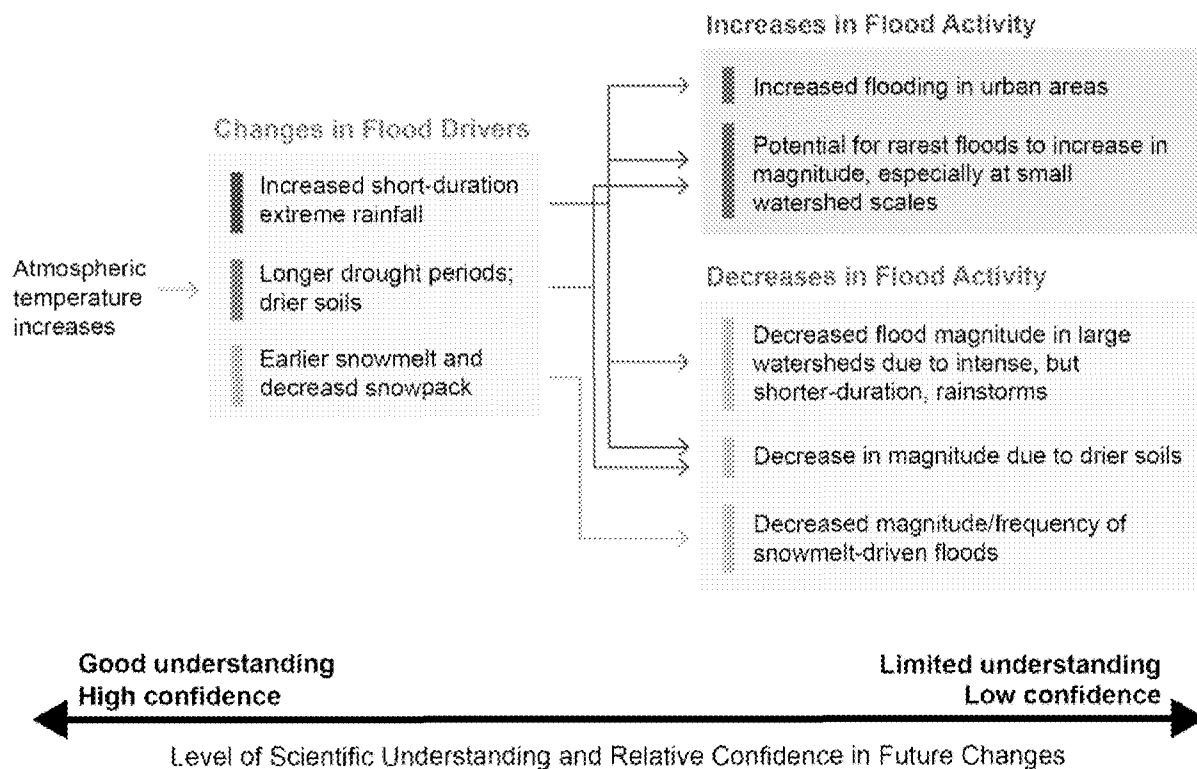
CAPTION: Rivers and streams integrate and reflect climate change impacts to the water cycle (Figures 4.3–4.6). Under the intermediate emissions scenario (RCP 4.5), projections of annual runoff vary geographically depending on relative changes to precipitation, evapotranspiration, snow and ice, groundwater, and soil moisture. Runoff in this figure does not reflect human activities that modify streamflow. Decreases are projected in many parts of the Nation supplied by snow and glacier melt. Decreases are also projected for Hawai'i. Data not available for the US Caribbean. Source: University of Colorado Boulder, NOAA NCEI, CISESS NC.

Extreme Events: Floods and Droughts

Floods are driven by complex interactions among precipitation, soil moisture, snowpack, and land cover (KM 2.2). However, estimates of events such as the 100-year flood typically rely on historical observations and assumptions of an unchanging climate (England et al. 2019; Office of Weather Prediction 2004). Whether these observations and assumptions can adequately reflect current and future flood conditions is an open question (Yu et al. 2019; Serinaldi and Kilsby 2015; Sivapalan and Samuel 2009).

Future flood frequency is challenging to predict (Figure 4.8; Yu et al. 2020; Hodgkins et al. 2019). For example, some extreme precipitation events will be buffered by future reductions in soil moisture, which will allow more rainfall to be absorbed (Wasko and Nathan 2019; Sharma et al. 2018; Grillakis et al. 2016). However, some areas are projected to see increases in floods from rain falling on snow (Il Jeong and Sushama 2018; Musselman et al. 2018), precipitation on wildfire-disturbed land (Ebel 2020; Williams et al. 2022), and loss of natural water storage in urban landscapes (Hettiarachchi et al. 2018).

Figure 4.8. Climate Change Impacts on Flood Magnitudes and Damages

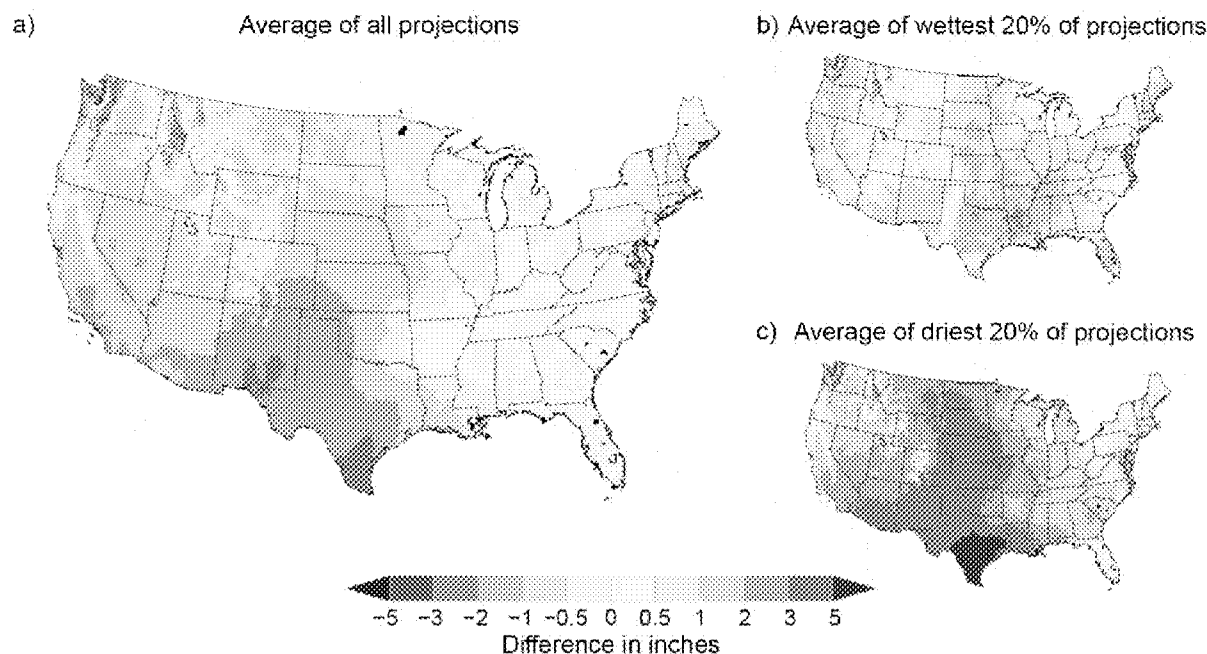


CAPTION: Floods result from complex interactions among extreme rainfall, soil wetness, and snowpack and snowmelt conditions. Increases in atmospheric temperature affect these processes differently; some increase flood potential while others decrease it. Adapted from Yu et al. (2020) under Creative Commons license [CC BY-NC 4.0](https://creativecommons.org/licenses/by-nc/4.0/).

Changes in future precipitation and temperature are expected to exacerbate drought across large portions of the US (Hobbins et al. 2019). Observed trends in drought (Figure A4.9) and climatic water deficit reflect these changes (Tercek et al. 2021), as do projections, with the strongest drying signal occurring in the Southwest (Figure 4.9; Overpeck and Udall 2020).

Figure 4.9. Projected Water Deficit

Projected Changes in Annual Climatic Water Deficit
2036–2064 relative to 1991–2020



CAPTION: Actual evapotranspiration (AET) is evapotranspiration (ET) limited by water availability—the less water available to be lost to the atmosphere, the lower the AET—whereas potential evapotranspiration (PET) is unconstrained by water availability. Climatic water deficit is the difference between PET and AET and is expected to increase across much of the Nation as temperatures drive increases in ET without compensating increases in precipitation. Data not available for the US Caribbean, Alaska, or Hawai'i. Source: University of Colorado Boulder.

1 **Box 4.1. Washington–California 2015 Snow Drought**

2 **Figure 4.10. Washington Apple Orchard Under Drought Stress**

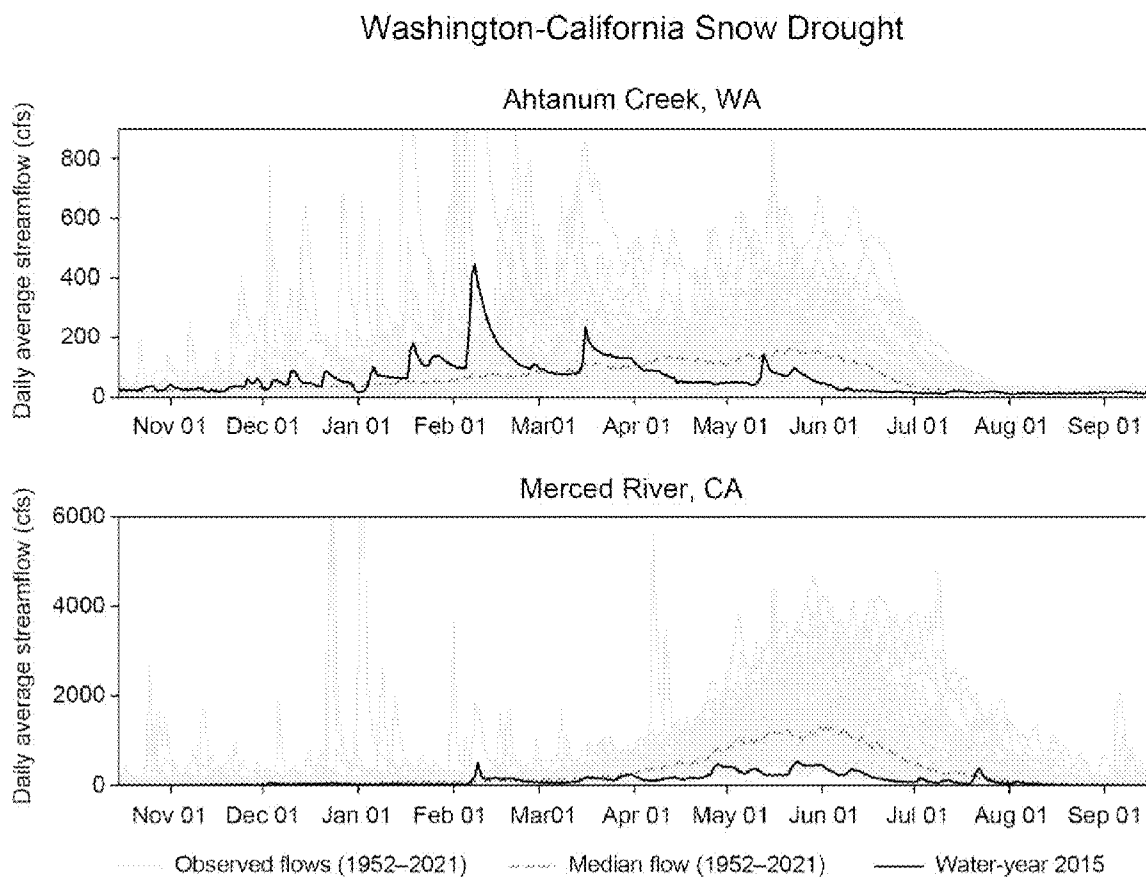


3
4 CAPTION: An apple orchard in the Roza Irrigation District in Washington shows extreme drought stress
5 in September 2015. Photo credit: © Sonia A. Hall.

6 Snow droughts occurred across much of the western coastal mountain ranges in the winter of
7 2014/15. However, the climatic causes of these droughts varied. Western Oregon and
8 Washington experienced a *warm* snow drought, wherein wintertime precipitation was 77%–
9 113% of normal, but elevated temperatures caused a larger proportion of that precipitation to fall
10 as rain, which reduced snow accumulation and increased winter snowmelt (Fosu et al. 2016). As
11 a result, wintertime streamflows were normal to high, but April to August flows were lower than
12 normal (Figure 4.11). By contrast, the California Sierra Nevada experienced a *dry* snow drought,
13 resulting in the shallowest snow volume ever recorded there (Belmecheri et al. 2016; Margulis et
14 al. 2016). Both the dry and the warm droughts caused strain on water rights holders. In Oregon
15 and Washington, crops—including valuable orchard crops that rely on water rights to divert
16 directly from streams—failed (Figure 4.10), but municipal water supplies that relied on storage
17 rights in reservoirs that had captured winter runoff were sufficient (Carlton 2015). In California,

1 total water supply was limited, resulting in severe or complete cutbacks to junior water rights and
 2 contract holders (Sugg 2018).

3 **Figure 4.11. Washington–California Snow Drought**



4
 5 CAPTION: The timelines compare the 70-year (1952–2021) median streamflow (dashed line) with the
 6 abnormally low 2015 summer streamflow (black line) that resulted from reduced snowpack during a
 7 warm snow drought (Ahtanum Creek) and a dry snow drought (Merced River). Daily streamflow for each
 8 of the years 1952–2021 (gray lines) is also shown. Merced River flows are lower year-round because
 9 little snow fell; Ahtanum Creek flows are shifted from summer to winter because little snow
 10 accumulated. Data source: USGS 2022. Figure source: Colorado State University.

11 [END BOX 4.1 HERE]
 12

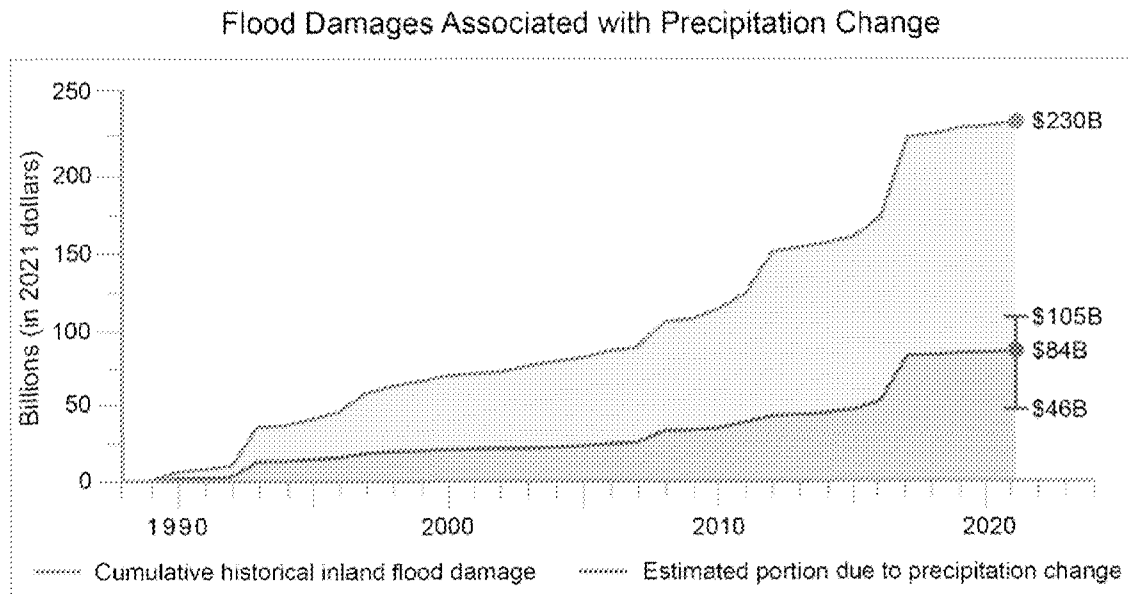
Key Message 4.2. Rising Risks, Disproportionate Impacts

Natural and human systems have evolved under the water cycle's historical patterns and cannot adapt quickly to rapid changes in patterns of droughts and floods (*high confidence*). Communities on the frontline of climate change—including many Black, Hispanic, tribal, Indigenous, and socioeconomically disadvantaged communities—are particularly at risk from changes to water quantity and quality due to the proximity of their homes and workplaces to hazards, limited access to resources and infrastructure, and cultural connections to water (*very likely, high confidence*).

Flood Impacts

Changes in extreme precipitation have increased economic damages from floods overall (Figure 4.12; Davenport et al. 2021).

Figure 4.12. Flood Damages Associated with Precipitation Change



CAPTION: Cumulative observed inland flood damages across the contiguous United States (gray) and estimated portion due to precipitation change (green) are shown for 1988–2021. Error bars show the 95% confidence interval for cumulative damages in 2021. Roughly 20%–46% of increases in observed flood damages can be attributed to upward trends in precipitation (assuming the same historical development patterns). Adapted from Davenport et al. (2021).

In urban settings, pavements, roofs, and compacted soils do not absorb water as effectively as natural landscapes, amplifying the effects of heavy precipitation and concentrating flooding. In rural settings, the relatively low amount of impervious land cover allows soils to hold more

1 rainfall. However, intensive agriculture can reduce infiltration capacity and increase runoff,
2 resulting in flooding.

3 Rising flood risks increase threats to water quality and ecosystems. As floodwaters flow over
4 normally dry areas, they transport debris, chemicals, bacteria, and other harmful contaminants
5 (Harris et al. 2021; Schaffer-Smith et al. 2020). High precipitation events can overwhelm
6 combined stormwater–sewer systems, leading to discharges of raw sewage into receiving waters
7 (Roseboro et al. 2021), and wells for drinking water can become contaminated from standing
8 floodwaters over wellheads and percolation into well-fields (Pieper et al. 2021). In farmlands,
9 high runoff can discharge fertilizer into streams and lakes, causing harmful algal blooms (Wells
10 et al. 2020).

11 Drought Impacts

12 “Drought” has long been challenging to define beyond “insufficient water to meet needs”
13 (Redmond 2002). Below-normal precipitation is usually part of drought, but there is growing
14 acknowledgement that higher temperatures can cause drought to develop, or to become more
15 intense than would be expected from precipitation deficits, because of increased atmospheric
16 demand for moisture—a phenomenon known as “hot drought” (Figure 4.13; Crausbay et al.
17 2020; Overpeck 2013). Above-normal temperatures also contribute to “flash drought,” which
18 develops quickly over a few weeks (Otkin et al. 2018; Svoboda et al. 2002) and “snow drought”
19 (Box 4.1). “Megadroughts” are events of extraordinary duration and severity (Cook et al. 2022).
20 Finally, “anthropogenic drought” describes drought caused by an unsupportable societal demand
21 for water (AghaKouchak et al. 2021).

22 Figure 4.13. Climate and Water Use Drive Drought

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23
24 CAPTION: A broader understanding of drought acknowledges that higher temperatures and human use
25 can exacerbate or even cause drought. Drought can occur whether precipitation decreases or remains
26 near normal, indicated by the dashed lines (left). Newer framings of drought highlight that it can
27 develop in a matter of weeks or last for decades (right). Adapted from Crausbay et al. (2020).

Between 1980 and 2021, drought and related heatwaves in the US caused \$291.1 billion in damages; only tropical cyclones and severe storms were more costly (NOAA NCEI 2022). Droughts often reduce agricultural productivity and strain water systems (Van Loon 2015; Boyer et al. 2013), driving shortages in water supplies and threatening hydropower generation (Turner et al. 2022; KM 5.1).

Drought stresses terrestrial and aquatic ecosystems (Crausbay et al. 2017) by leading to increased water temperature and salinity, reduced nutrients, lower oxygen levels, concentrated contaminants, loss of surface and groundwater connections, and declining productivity (EcoAdapt 2021; Poff et al. 2012). In addition, drought can exacerbate other disturbances such as insects and wildfire (Vose et al. 2016). Ecosystems can be resilient under normal climate variability, but recovery after drought in a changed climate may not be possible, leading to the loss of ecosystem services and loss or shifts of both native and invasive species (Höök et al. 2020; Johnson et al. 2016).

Drought conditions have historically resulted in increased groundwater pumping, a practice projected to increase with climate change (Bloomfield 2019; Hanson et al. 2012; Scanlon et al. 2012). Declining groundwater levels due to pumping can reduce streamflow (Jasechko et al. 2021; Figure 4.14). Additionally, as pumping increases, so does land subsidence (Galloway et al. 1999).

Figure 4.14. San Pedro River, Arizona

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CAPTION: The San Pedro River in Arizona has been depleted by groundwater pumping nearby, drying up wetlands and wildlife habitat (Borunda 2019). Photo credit: Will Seberger/ZUMA PRESS Inc./Alamy.

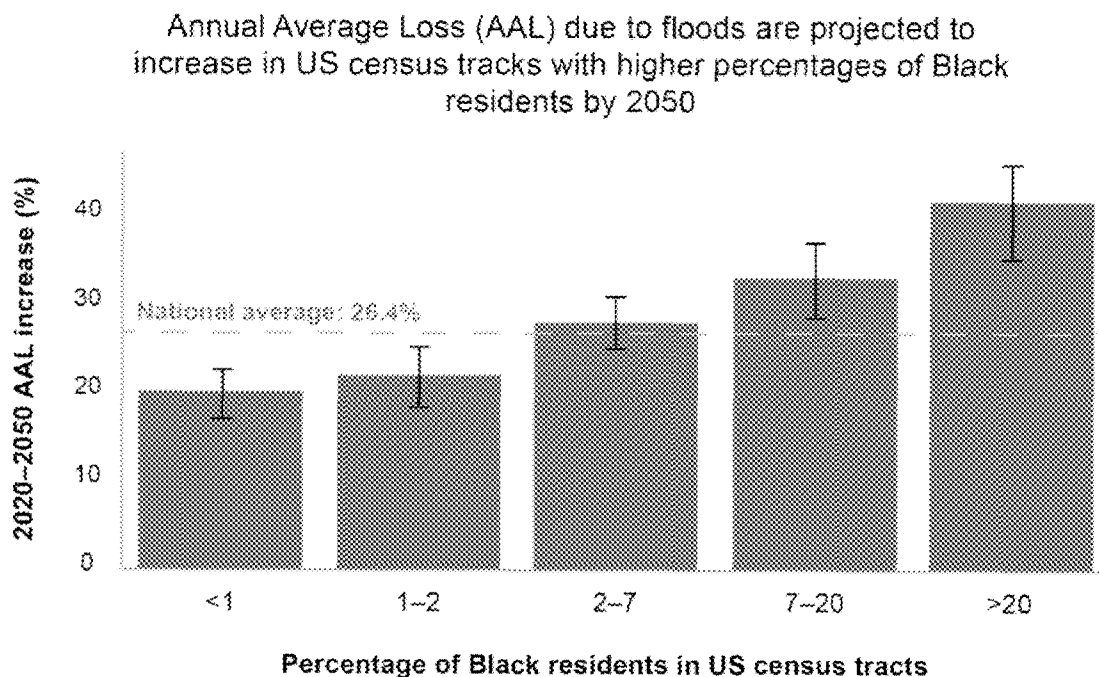
Disproportionate Impacts

Climate change creates unequal burdens on people and communities (Nelson et al. 2022; Goldsmith et al. 2021; Climate Justice Working Group 2017). People who live along coasts, rivers, and in inner cities, or who work in agriculture and fisheries, have increased exposure to water-related hazards (Edmonds et al. 2020; Thiault et al. 2019; Reckien et al. 2017). Older

adults, children, marginalized groups, and residents of low-income neighborhoods and rural areas are at greatest risk of exposure to pathogens and pollutants from climate change–driven impacts to water quality (Leffers 2022; EPA 2022; Ebi et al. 2021).

Many tribal and Indigenous communities reside in areas subject to coastal and riverine flooding and risk displacement from lands with cultural significance (Bronen et al. 2018; Marino 2015; Petrasek MacDonald et al. 2015). Neighborhoods that are home to racial minorities and people with low incomes have the highest flood exposures in the South (Tate et al. 2021), while Black communities are projected to bear a disproportionate share of future flood damages (Figure 4.15; Box 4.2; Wing et al. 2022). Drought can also have unequal impacts depending on economic sector, access to water resources, ability to irrigate, reliance on hydropower, and socioeconomic status (Engström et al. 2020).

Figure 4.15. Future Flood Damages Will Be Shared Disproportionately



CAPTION: Flood damage in census tracts with a Black population of at least 20% is projected to increase at roughly twice the rate of that in tracts with Black populations making up less than 1% of population. Adapted from Wing et al. (2022).

Box 4.2 Climate Change, Urban Flooding, and Inequality

Hurricane Harvey dropped record-breaking rainfall onto the Houston metropolitan area in August 2017 (Figure 4.16). Exacerbated by extensive urbanization, the flooding killed more than 100 people and caused an estimated \$125 billion in damages (National Hurricane Center 2018). Rainfall was estimated to be 8%–19% heavier than it would have been absent human-caused warming (Risser and Wehner 2017; Van Oldenborgh et al. 2017), leading to a 33%–80%

increase in flood damage (Frame et al. 2020). As with recent floods elsewhere, many of the flooded properties were located outside FEMA's designated 100-year floodplains and not covered by federal flood insurance. Such properties were disproportionately inhabited by Black and Hispanic residents (Smiley 2020). Disabled people and residents of subsidized housing were also disproportionately affected (Chakraborty et al. 2021, 2019).

Figure 4.16. Flooding in Houston from Hurricane Harvey



CAPTION: Flooding from Hurricane Harvey inundated residential neighborhoods near Interstate 10 in Houston, Texas. Photo credit: Marcus Yam/Los Angeles Times via Getty Images.

[END BOX 4.2 HERE]

Across the Nation, infrastructure is aging and deteriorating (KM 12.2), increasing the risks of contamination and delivery of non-potable water (Vacs Renwick et al. 2019). These deficiencies increase tribes' vulnerability to flooding, drought, and waterborne diseases; threaten the social, physical, and mental well-being of tribal communities; and impair their ability to thrive (KM 16.3; NCAI 2017; Cozzetto et al. 2014). The Indian Health Service has identified more than 400,000 American Indian/Alaska Native (AI/AN) homes requiring some form of sanitation facility improvement (Figure 4.17; IHS 2019).

1 **Figure 4.17. AI/AN Homes Requiring Water and Sewer System Improvements**

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2
3 **CAPTION:** Water infrastructure supporting tribal and Indigenous peoples is particularly ill equipped to
4 handle increases in flooding and drought. The Indian Health Service (IHS) is the federal agency
5 responsible for delivering health services to American Indians and Alaska Natives (AI/AN). As part of this
6 federal responsibility, the IHS Sanitation Facilities Construction Program provides AI/AN homes and
7 communities with essential water supply, sewage disposal, and solid waste disposal facilities. IHS
8 maintains the Home Inventory Tracking System (HITS), a database of AI/AN homes requiring sanitation
9 facility improvements within IHS service areas. The figure shows a map of the continental US with
10 colored dots showing sanitation deficiency levels across the country. Sanitation deficiencies range from
11 Level I to Level V, and are defined as follows:

- 12 • Level I: An Indian tribe or community with a sanitation system that complies with all applicable water
13 supply and pollution control laws, and in which the deficiencies relate to routine replacement, repair, or
14 maintenance needs (yellow dots).
- 15 • Level II: An Indian tribe or community with a sanitation system that complies with all applicable water
16 supply and pollution control laws, and in which the deficiencies relate to capital improvements that are
17 necessary to improve the facilities in order to meet the needs of such tribe or community for domestic
18 sanitation facilities (yellow-orange dots).
- 19 • Level III: An Indian tribe or community with a sanitation system that has an inadequate or partial water
20 supply and a sewage disposal facility that does not comply with applicable water supply and pollution
21 control laws, or that has no solid waste disposal facility (orange dots).
- 22 • Level IV: An Indian tribe or community with a sanitation system that lacks either a safe water supply
23 system or a sewage disposal system (orange-red dots).
- 24 • Level V: An Indian tribe or community that lacks a safe water supply and a sewage disposal system (red
25 dots).

26 Data for Hawai'i and the US Caribbean not available. Adapted from Tanana et al. (2021), Figure 9.

Key Message 4.3. Slow Progress Toward Adaptation

The ability of water managers to adapt to changes has improved with better data, advances in decision-making, and steps toward cooperation. However, infrastructure standards and water allocation institutions have been slow to adapt (*high confidence*), and efforts are confounded by wet and dry cycles driven by natural climate variability (*high confidence*). Frontline, tribal, and Indigenous communities are heavily impacted but lack resources to adapt effectively, and they are not fully represented in decision-making (*high confidence*).

Approaches to Management and Planning

Uncertainty has always factored into water resources planning, but as the water cycle intensifies, water supply and extreme event uncertainties have increased. Responses to these growing uncertainties include nature-based solutions (KM 8.4); water conservation and reuse (Chang et al. 2018); decision science (Smith et al. 2022; Woodhouse et al. 2021); reservoir optimization (Goharian et al. 2018; Steinschneider et al. 2015); improved weather and streamflow forecasts (Towler et al. 2022); municipal planning (Kim et al. 2022; 2017; Salinas Rodriguez et al. 2014); adaptive management systems (Gorelick et al. 2020); stakeholder–scientist partnerships (Misra et al. 2021); and adaption guidance (KM 31.4; WUCA 2021; Vincent et al. 2018).

Conflict, Competition, and Collaboration

Climate change impacts to water supplies can result in competition, collaboration, or conflict. Traditionally, water disputes in the western US are resolved through litigation (Grafton et al. 2011). However, under current severe drought conditions, water interests in the Colorado River basin, including Mexico, are struggling to avoid litigation through negotiated settlements and voluntary use reduction (Fleck and Castle 2022; Juricich 2020; Sullivan et al. 2019). Some of these efforts include tribes and other water users who have traditionally been excluded from participation in negotiations, although representation remains uneven (Karambelkar and Gerlak 2020).

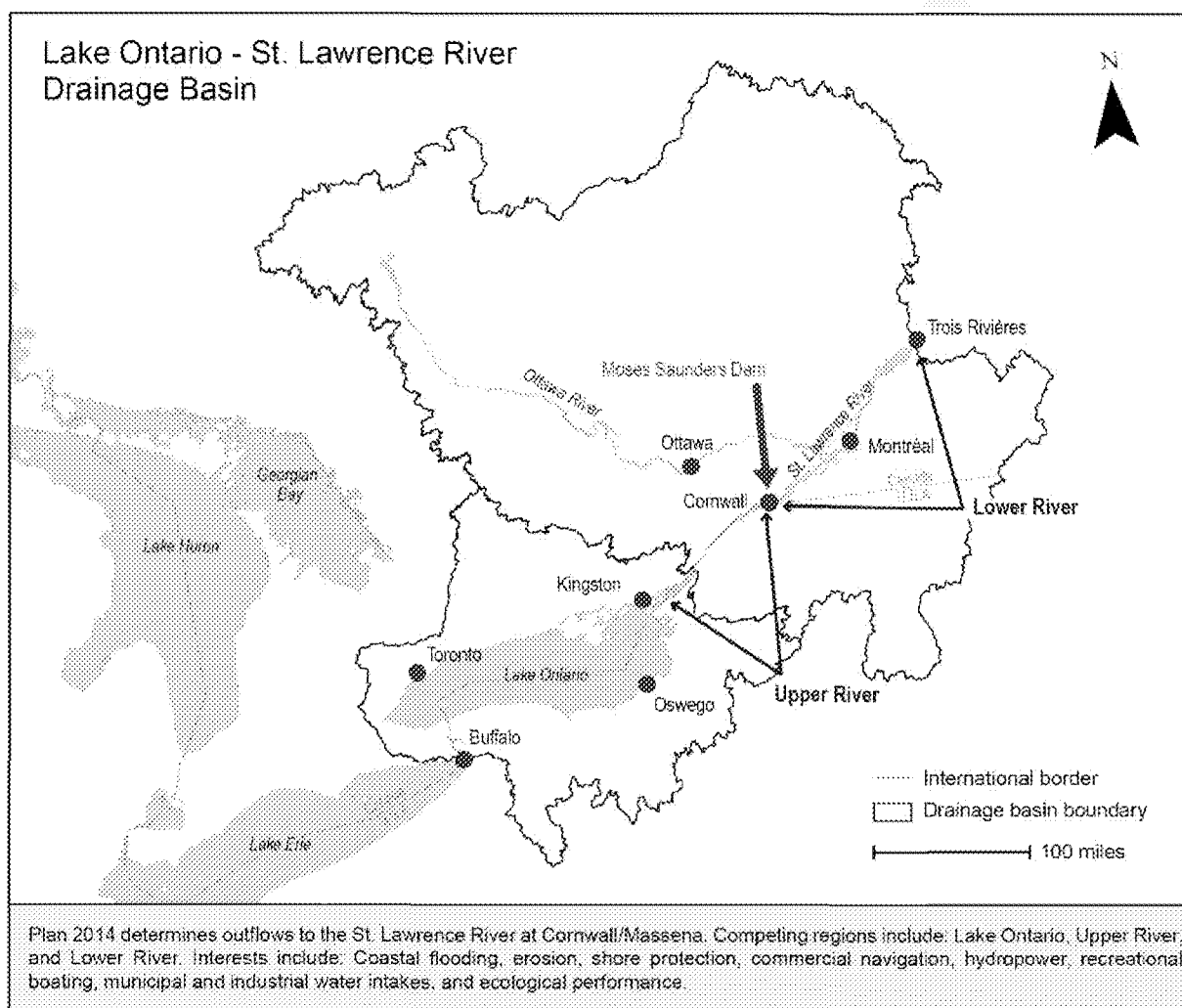
In areas where flood risk is increasing, collaboration on flood hazard management at regional scales has become more urgent, as cooperation can provide solutions that are not available at the local scale (Box 4.3). This is especially true in the Midwest, where flooding is often regional and local solutions can push flood risks downstream (Reed et al. 2020).

Box 4.3 International Cooperation in the Great Lakes

The Great Lakes, which contain the largest quantity of surface freshwater on Earth, are shared by two Canadian provinces, eight US states, and many sovereign tribes and First Nations. Although ripe for conflict and competition, the waters have been equitably shared under the 1909 Boundary Waters Treaty (International Joint Commission 2016) for more than a century. In 2017, a management plan regulating Lake Ontario’s levels and outflows was implemented

(Figure 4.18; International Joint Commission 2014). It was the culmination of over 16 years of scientific study, public engagement, and governmental review. Among other goals, the plan balances flooding along the lake's New York and Ontario shorelines against flooding downstream on the St. Lawrence River at Montreal, Quebec. It aims to restore the health and diversity of coastal wetlands, protect against extreme high and low water levels, and perform under changing climate conditions.

Figure 4.18. Managing the Waters of Lake Ontario and the St. Lawrence River



CAPTION: Geographic setting for an international plan between the US and Canada to cooperatively manage Lake Ontario. The plan balances interests upstream of the Moses Saunders Dam with downstream interests. Adapted from International Joint Commission (2014).

[END BOX 4.3 HERE]

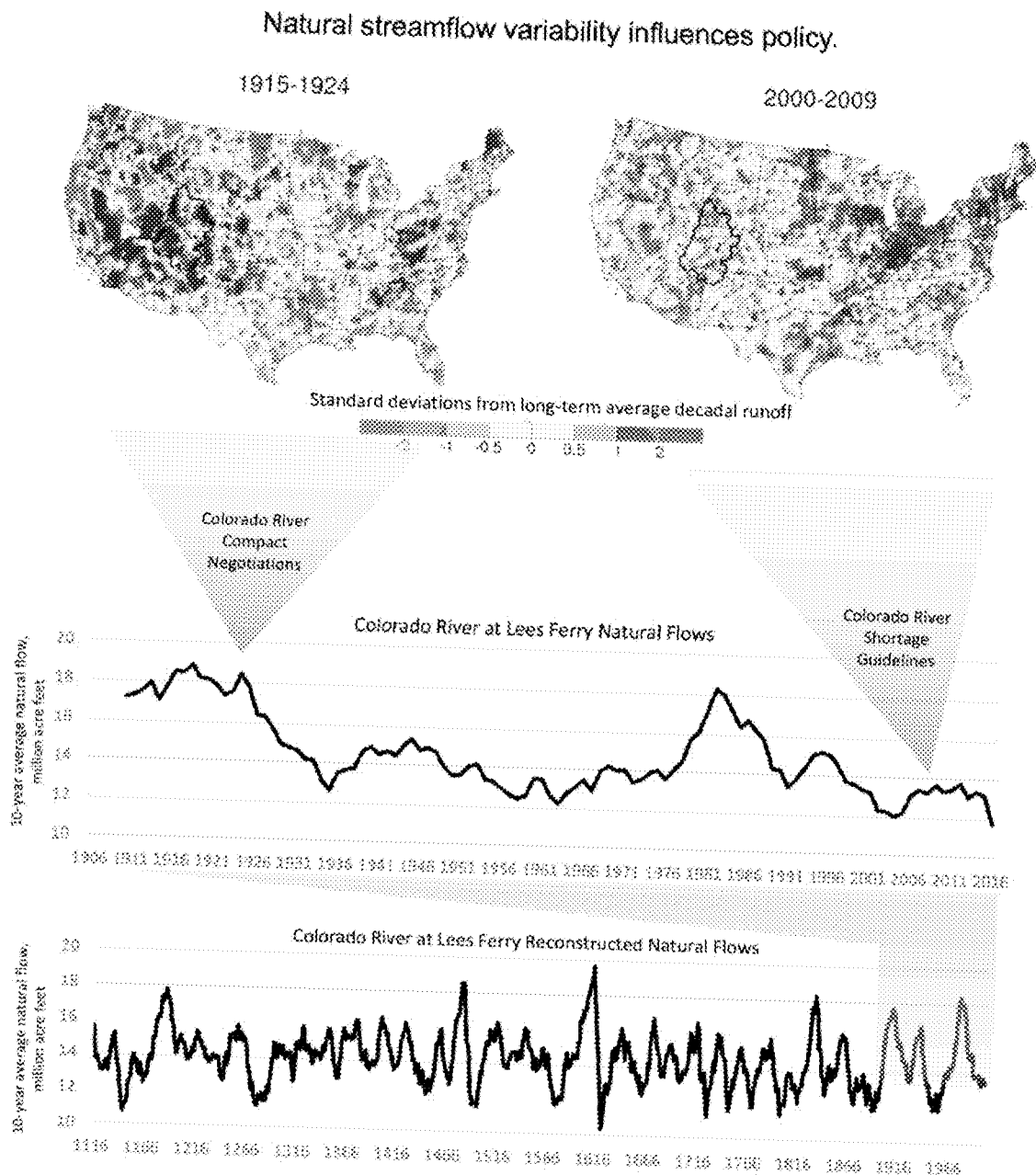
1 **Adaptation Constraints**

2 Climate change is overtaking the speed of policymaking (Hoylman et al. 2022; Xu et al. 2018),
3 making risk reduction a continual exercise in catching up. For example, current rates of
4 precipitation change outpace the regulatory changes needed to cope with them. Rainfall metrics
5 for design and decision-making are widely outdated (Wright et al. 2019; Lopez-Cantu and
6 Samaras 2018); updating these metrics is essential to protecting communities. While there have
7 been recent advances in data collection, statistical methods, climate modeling, and weather
8 forecasting, progress is difficult, in part because regulations, codes, and standards involve
9 competing interests and often span multiple jurisdictions.

10 **Natural Variability's Effect on Policy**

11 Streamflow fluctuations due to natural variability (KM 3.3) are large and can obscure long-term
12 climate changes. Natural variability brought perhaps the wettest period in the past 1,200 years to
13 the Colorado River in the early 20th century (Figure 4.19). The Colorado River Compact,
14 negotiated in that period of relative abundance, allocated far more water than the river provides
15 (Kuhn and Fleck 2019). The current 22-year drought (Williams et al. 2022) in the basin has
16 triggered unprecedented restrictions on water use and is leading to more realistic policy
17 discussions (Fleck and Castle 2022). However, natural variability will lead to prolonged wet
18 periods again, though diminished by higher temperatures, suggesting that durable and realistic
19 long-term perspectives are necessary for robust policy development.

1 Figure 4.19. Natural Streamflow Variability Influences Policy



2
3 CAPTION: Natural variability in streamflow can promote urgency or complacency in long-term planning.
4 The figure shows streamflow variability in both space and time: across the country between two
5 decades, and across time with estimates of Colorado River flows from historical observations and tree-
6 ring reconstructions. Wedges point to two negotiated policy events. Sources: Maps: adapted from
7 Livneh et al. (2015). Center time series: adapted from Bureau of Reclamation 2022. Lower time series:
8 adapted from Meko et al. (2017).

Adaptation Challenges Faced by Tribal and Indigenous Communities

To address water-related climate impacts, tribes have voiced the need for climate impact assessments as a first step to resilience planning and have identified information about climate change impacts to water as a top priority (Fillmore and Singletary 2021). Many Indigenous communities lack data on water quality despite disproportionately experiencing water quality deficiencies (Conroy-Ben and Richard 2018). Water quality data applicable to tribal water management decisions are the data type most needed (followed by streamflow, temperature, precipitation, snowpack, and soil moisture), but are not readily available through federal sites (Fillmore and Singletary 2021).

Food security, protection of traditional knowledge, and tribal capacity to implement adaptation plans, monitor and collect data, and conduct climate vulnerability assessments are also high priorities. Federally recognized tribes are eligible for federal assistance with climate change adaptation, but they face hurdles accessing these limited resources, including agency requirements (e.g., funding matches), lack of tribal capacity, and navigating interagency processes.

Progress and Gaps in the Quality and Usability of Information

Water resources planning continues to be informed by past hydrologic records that do not reflect the impacts of climate change. Although some federal, state, and larger local agencies do use climate projections in planning, projections of precipitation, streamflow, and water demand at the scale of local watersheds are rarely available. Using projections is also costly because tools and techniques are specialized and not standardized. Finally, climate models project a wide range of possible futures, requiring planners to use their best judgment about how to apply the information.

Data are foundational to adaptation. State and federal agencies have been collecting valuable climate and hydrology data for over a century, but these data are sparse in lightly populated and lower-income areas. Increasingly, modeling and remote sensing data are filling the gaps. High-resolution elevation and environmental data collected from airborne and spaceborne platforms provide detailed topography and hydrological information that can be used to map flood hazards and snowpack (Margulis et al. 2019; Painter et al. 2016) and refine real-time snow simulation (Pflug, et al. 2022). Evapotranspiration is being estimated using satellite remote sensing combined with vegetation models (Melton et al. 2021), providing early warning of emerging droughts (Senay et al. 2020), and satellites are now being used to detect groundwater depletion trends (Tapley et al. 2019). Nevertheless, expanding direct observational data collection is still key to tracking environmental conditions and supporting development and testing of remotely sensed data and models.

1 **Traceable Accounts**

2 **Process Description**

3 With support from the chapter point of contact and the federal coordinating lead author, the
4 chapter lead author selected authors for their expertise in assessing climate impacts to the
5 Nation's surface and groundwater resources and the consequences of those impacts to human
6 and natural systems, with an emphasis on the authors' ability to bring diverse perspectives to the
7 team. The team comprises experts drawn from several regions across the country who work
8 under various employment types (i.e., private business, academic institutions, and local, state,
9 and federal governments), come from diverse backgrounds, and represent a range of
10 combinations of age and gender. The team met virtually multiple times to scope the chapter, with
11 each author offering their own priorities about what a chapter about the Nation's water resources
12 should cover, taking into consideration the goals of the assessment, what has been covered in
13 previous National Climate Assessments (NCAs), and the topics of the other 31 chapters in
14 NCA5. The team's discussions revolved around these questions: How are changes in climate
15 influencing water input volume and movement? How are extremes and the notion of extremes
16 changing? How are changes in climate stressing both natural and human-made systems? What
17 are the environmental justice considerations and the distribution of impacts? Are current climate
18 data and tools adequate for decision-makers? And what are the interconnected climate risks?
19 With these questions in mind, the team iteratively developed a draft outline for the chapter. That
20 outline was made available online for public review and comment. The team presented and
21 participated in a virtual, public, four-hour workshop and discussion, collecting comments and
22 suggestions for the chapter from workshop participants. Workshop comments and formally
23 submitted comments were taken into consideration in development of the chapter text.

24 **Key Message 4.1. Profound Changes to the Water Cycle**

25 **Description of Evidence Base**

26 There is general consensus that warming temperatures will enhance evaporative demand across
27 the Nation; however, uncertainties in vegetation response to warming reduces confidence in
28 evapotranspiration (ET) projections. The degree of observed change in ET is also less certain,
29 particularly east of the Rocky Mountains, and ET projections can differ when variables other
30 than temperature are considered. Shifts in ET will alter the amount of water that recharges to our
31 groundwater systems; however, changes in recharge have not been well quantified.

32 There is widespread consensus that increases in temperature will decrease the proportion of US
33 precipitation that falls as snow, decrease snow extents, advance the timing of snowmelt rates and
34 pulses, and increase the prevalence of rain-on-snow events.

35 Since parts of Alaska and the highest elevations in the contiguous United States may be cold
36 enough to sustain snowfall in future climates, some studies have projected increases in snow

1 volume in these locations with future increases in precipitation. However, these increases in
2 snow are expected to be vastly outweighed by the future decreases in snow elsewhere,
3 particularly across the western United States and by the late 21st century for all intermediate
4 (RCP4.5 and SSP2) and higher emissions scenarios.

5 **Major Uncertainties and Research Gaps**

6 Uncertainties stem from future projections of climate, especially precipitation. This may be
7 particularly true for late-21st-century projections that are dependent on the degree to which
8 societies will respond to climate change. The literature employs different projections and
9 emissions scenarios, as well as metrics and measurements that vary in their degree of climate-
10 sensitivity, resulting in studies that are not always directly comparable.

11 Understanding recent and potential future flood responses to climate change is difficult for
12 several reasons. Floods are the product of complex subseasonal to interannual interactions
13 between rainfall, soil moisture, evapotranspiration, snowpack/melt, and other processes. Isolating
14 climate change impacts on flooding is further complicated by the hydrologic “replumbing”
15 wrought by urbanization and dams. For these reasons, the translation of rainfall trends into flood
16 changes is complex and poorly understood. Nationwide examination of historical flood records
17 has concluded that climate influences have been relatively limited, contradicting earlier studies
18 that argued that the largest floods have increased in severity. This latter argument is further
19 contradicted by evidence that floods in the central United States have become more common but
20 not more intense.

21 However, major floods are by definition rare, making detection and attribution of changes
22 difficult. Thus, a lack of statistically significant trends in observed floods does not necessarily
23 indicate that such events are not changing. Indeed, a relatively limited number of geographically
24 focused case studies have painted complex pictures of climate-related flood changes that are
25 lacking in broader regional and national analyses. Additional place-based case studies—as
26 opposed to regional- or national-scale analyses—could help unravel the complex interactions
27 between climate and non-climate flood drivers.

28 Given the first-order influence of temperature and precipitation change on snowfall, there is low
29 uncertainty in the assessment of future US snow cover, snow volume, and snow persistence.
30 However, there is some disagreement in the literature about the extent and direction (positive or
31 negative) of change in surface water availability with future changes in climate. Changes to total
32 runoff are modulated by the frequency, severity, and phase of precipitation events, as well as
33 future changes to land surface characteristics and the resulting movement of water to
34 evapotranspiration, groundwater recharge, and streamflow. Existing studies indicate both
35 increases and decreases in future runoff for different US hydroclimatic regimes.

36 In particular, there is uncertainty in the degree to which temperature may impact flow in some
37 major river systems in the West, as well as disagreement about the degree and even direction of
38 recent changes in potential evapotranspiration over much of the United States. Significant

disagreements in the direction of soil moisture trends remain, largely because it can be challenging to estimate with remote sensing or models, and the existing in situ soil moisture monitoring network is insufficient.

Similarly, there is uncertainty in both the magnitude and direction of groundwater storage changes. This is due to uncertainty in both the human response to changing climate conditions and research gaps in quantifying natural groundwater recharge. Groundwater pumping is controlled by a myriad of human factors such as water policy, crop choices, and irrigation technology. While it is well established that warmer temperatures can increase irrigation demand, the extent to which this actually results in additional groundwater pumping will depend on agricultural management practices and policy. Groundwater recharge is similarly uncertain. Projected increases in large precipitation and flooding events are likely to increase recharge (known as episodic recharge events). However, the quantity of this recharge is less certain and highly dependent on the nature and timing of the storms that occur. Also, while increases in recharge may be counteracted by changes in plant water usage and snowpack that can decrease natural recharge, the magnitude of these recharge changes has not been well quantified. Separating the impacts of groundwater pumping from climate trends is particularly challenging due to a lack of long-term groundwater monitoring wells.

Description of Confidence and Likelihood

There is *high confidence* that the changes in precipitation, soil moisture, and snow processes are having, and will continue to have, large impacts to humans and ecosystems. Though there are regional differences, there is *medium confidence*, as indicated by current trends and climate model projections, that there will *likely* be more precipitation in parts of the country and more extreme precipitation events nationwide. Based on current trends and climate model projections, there is *high confidence* that warming temperatures will *very likely* cause soils to dry, increasing the demand for surface and groundwater for crops and human use. There is *high confidence* that the extent, volume, and duration of snow cover and melt upon which human and natural systems rely are likely being reduced by warming.

Key Message 4.2. Rising Risks, Disproportionate Impacts

Description of Evidence Base

Observational records now span time periods long enough to evaluate changes in the volume, variability, and timing of water availability. The magnitude of these changes, and their agreement with model projections, vary with hydroclimate regimes across the United States. Natural water systems are susceptible to changes in climate, increasing the occurrence and/or severity of extreme events like floods and droughts. Studies have found that the risk of episodic or long-term hydrologic hazards varies based on location.

While it has been difficult to establish clear linkages between increases in extreme precipitation and trends in “traditional” measures of flood activity such as peak streamflow rate, attribution studies have apportioned some of the historical increases in flood damage to precipitation change. It is probable that many of these increases have been concentrated in urbanized watersheds, which are more sensitive to rainfall than rural and natural settings. Flood vulnerability, including in urbanized areas, tends to be concentrated in historically marginalized and socioeconomically disadvantaged neighborhoods. There is increasing consensus that systematically disadvantaged communities have been and will continue to be most impacted by these hazards, due to factors such as inadequate climate/hydrological monitoring, deferred infrastructure maintenance, and insufficient access to recovery resources.

There is ample literature describing the impacts of floods, fires, and drought events on a wide variety of water quality hazards. These studies provide insights into impacts to water quality hazards from intensified events due to climate change, and studies specific to climate change impacts on water quality are becoming more prevalent. There are some reports of specific benefits to contaminant concentrations from increased or decreased precipitation, but there is no consensus that water quality will improve with climate change. There is consensus that negative impacts will be felt disproportionately among marginalized and low-income people.

Major Uncertainties and Research Gaps

There is moderate uncertainty about the degree to which land surface changes will drive nonstationary changes to the volume and timing of water resources. There is a lack of research on the linkages between climate change and flooding. There is uncertainty about the extent to which traditional design storms—that is, storms of particular intensity and duration, used in floodplain and built environment planning—and flooding assumptions based on older observations adequately reflect current and future flood conditions.

Description of Confidence and Likelihood

There is *high confidence*, based on historical, archaeological, and paleoecological records and reconstructions, that natural and human water systems have evolved or been designed to withstand relatively predictable ranges of weather and climate conditions. Climate change, however, imparts a number of important shifts in local and regional hydrologic cycles, including increases in the frequency, severity, and duration of extreme events such as floods and droughts. Based on the vast literature documenting current, disparate impacts to frontline communities from floods, droughts, and the exposures they bring, there is *high confidence* that frontline communities will *very likely* be at disproportionate risk from water-related hazards exacerbated by climate change.

Key Message 4.3. Slow Progress Toward Adaptation

Description of Evidence Base

A wide array of literature over the past decade has identified the safety and economic risks posed by aging water systems and changing hydrology. Since the publication of the NCA4, expanded data collection, improved climate projections, and better short to mid-term forecasts support better water resource management and planning. However, local water resource managers are still struggling to find accessible, usable science and data at the appropriate spatial scale, and they continue to rely on past historical records that often do not reflect current and future water availability and timing. A growing literature focuses on providing scientific information that is more usable for water resource planning and management. There has been less work in assessing success and evaluating how equitable these approaches have been.

A number of retrospective reviews highlight the omission of frontline, tribal, and Indigenous voices and benefits from water projects. Long-standing legal entitlements, established before climate change was a consideration, are well documented. The bulk of senior water rights and legal entitlements in the West are held by tribes and agricultural water users but governed by state and federal decrees, agreements, and compacts that were not written to be flexible or responsive to a changing climate. Current literature is documenting these barriers and assessing emerging approaches to work past them.

Disaster management literature contains many examples of public complacency and/or urgency in preparing for extreme events. Reviews document that drought preparation, in particular, is more reactive to current conditions than flood preparation, and is hampered by uncertainties in future conditions.

Major Uncertainties and Research Gaps

Building climate resilience in hydrologic systems is challenging given the high uncertainty of climate variability and change. Gaps in actionable local-scale water data are particularly problematic, especially translating projections from global climate models to the regional and local level. System-level approaches and the use of resilience metrics are also areas ripe for improvement.

There is moderate uncertainty about the degree to which changes to land surface characteristics will drive changes to the volume and timing of water resources, and the degree to which existing infrastructure and historically defined allocations will be able to adapt. A large part of this uncertainty is related to how quickly human actions and policies react to hydrologic hazards.

Description of Confidence and Likelihood

Rising water-related disaster costs, communities ill-prepared for floods and droughts, and basin water users deferring difficult water allocation decisions are just a few of the pieces of evidence leading to *high confidence* that adaption efforts are proceeding slowly relative to the rate of climate change and that this is partly due to natural climate variability masking long-term changes. The history of water resources decision-making rarely includes participation by frontline, tribal, or Indigenous individuals or communities. Their exclusion from negotiations,

compacts, decrees, and other allocation actions is evidence that there is *high confidence* that frontline, tribal, and Indigenous communities have not had full representation in water resources decision-making in the past, despite suffering the impacts of those decisions.

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From: John Christy <climateman60@gmail.com>
Sent: Tuesday, June 3, 2025 1:09 PM
To: Ross McKittrick
Cc: Steven Koonin; Travis Fisher; Judith Curry; Roy Spencer; Josh Loucks
Subject: Re: an early take on NCA5 Chapter 1

Steve

I went through the NASEM comments. The only statements relative to Fig. 2.8 (which was 2.7 in the reviewed version) were that the Pacific Islands weren't included and the labels/caption were too technical - not a single comment critical of or even curious about the science (that I could find). The discussion did not touch on the issues I raised. In fact, the reviewers seemed to encourage more dramatic statements. Then on pg 56 of the Review, they speak as if the model output is real, stating, "the Committee suggests that slight wording changes such as "northern and eastern states will see more precipitation and southern states will see less" would make these statements more accurate and effective." It sounds like they want to insist that the model projections of precipitation are very useful. I don't see a statement that says, "Given the unknown evolution of the climate system due to natural variations alone, combined with the disparity among the models regarding long-term changes in precipitation, we really can't say much about the future, except that new extremes for several places and metrics will occur that will exceed those experienced in the past 130 years."

John C.

On Tue, Jun 3, 2025 at 11:17 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:
Turns out I had 3rd Order Drafts of the NCA5 ch's 0,1-4 and 9; and even submitted comments on them (I'd forgotten). I never looked up how they replied to my comments.

On Tue, Jun 3, 2025 at 12:08 PM Steven Koonin <steven.koonin@gmail.com> wrote:

If we're going to criticize the peer review process (and I think we should), we've got to look at what the NASEM review said (or didn't say) about specific points and how USGCRP responded (or not) to them.

To do that, we need the report of the NASEM review and the USGCRP response (both of which I've sent around previously but also attached again here). But to match page and line references, **it would also be very helpful to have the draft NCA5 that NASEM reviewed.** That's no longer available on the web (or at least I couldn't find it), but perhaps one of you has a copy?

SEK

From: John Christy <climateman60@gmail.com>
Sent: Tuesday, June 3, 2025 11:24 AM

To: Ross McKittrick <ross.mckittrick@gmail.com>

Cc: Travis Fisher <travis.scott.fisher@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Judith Curry <curry.judith@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>

Subject: Re: an early take on NCA5 Chapter 1

All

Though we haven't settled on a battle plan for this second report, I was under the impression we would describe in general why NCA5 is junk-science (though that might disparage the term junk) and then provide examples from the report. With that in mind, this is what I had drafted for the extreme precipitation events - about which NCA5 made (and is making) a big deal.

John C.

On Tue, Jun 3, 2025 at 9:56 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

I'm happy to have Seth join us. If you send me his email I can add an invitation.

On Tue, Jun 3, 2025 at 10:09 AM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

Hi all,

I'm relaying information from a call I had last night with Audrey Barrios (senior advisor to the Secretary) and a call I had this morning with Lynne Parker (Principal Deputy Director at OSTP). Regarding authorship, this document should be written by you all (or a subset, if needed), and OSTP feels strongly that it should be published by the new Executive Director (Interim, if needed) of the USGCRP. I realize we don't know which specific person that will be yet, but that's how we should approach this work. I can share more details on the call this afternoon.

I also want to share the good news that we now have the assistance of a sharp attorney from DOE's Office of General Counsel. His name is Seth Cohen, and he comes highly recommended (litigation experience, clerkships at two different circuit courts, etc.). He can help us connect the dots between the GCRA statute, the executive order, the DOE report, and recommendations for moving forward (improving NCA 6 or whatever we're calling the next iteration). Would you all be comfortable having Seth join the call this afternoon, or should we hold off on introducing him to the team?

Best,

Travis

On Mon, Jun 2, 2025 at 10:37 PM Travis Fisher <travis.scott.fisher@gmail.com> wrote:

I'm happy to adjust as needed, but 3pm ET tomorrow works for me.

Regarding the what and the why of the task, we can discuss more details on the call, but my understanding is that we should critically review NCA 5 (at whatever level of detail is feasible in a period of a couple of weeks) through the lens of the statute, the executive order, and the DOE report.

As of right now, we should write this document as a response to a request from OSTP, along the lines of the scoping memo Ross shared. There is a chance OSTP might want to claim authorship, but my hunch is that whatever you all produce next will be another group report with each of your names on it.

The next best alternative is for one of you to take the helm at GCRP and publish the next document as something of a policy statement by the new GCRP director. (That's actually my first-best approach, but I completely understand if it's too big of an ask or if certain members of this group are too Canadian.)

On Mon, Jun 2, 2025 at 9:51 PM Ross McKittrick <ross.mckitrick@gmail.com> wrote:

Sent a meeting link for 3 PM. I couldn't remember what time we agreed to and I know Roy can't be there but I thought it was around 3.

On Mon, Jun 2, 2025 at 8:24 PM Steven Koonin <steven.koonin@gmail.com> wrote:

At least some politicians are trained as lawyers and understand the concepts of evidence, proof, etc. I think we could reach them. And in the current political/culture climate, everyone is suspicious of being lied to. Worth a try, in my opinion (and experience).

Anyway, we should discuss on tomorrow's call. Do we yet have a time and video link?

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Monday, June 2, 2025 7:54 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Josh Loucks <loucksj14@gmail.com>
Subject: Re: an early take on NCA5 Chapter 1

well try to convince a politician of that!

Maybe we should just focus on recommendations for future NCAs

Just focusing on what they selected for the report summary isn't too helpful IMO.

I am still lost as to what we are supposed to be doing and why

On Mon, Jun 2, 2025 at 1:39 PM Steven Koonin <steven.koonin@gmail.com> wrote:

"If I were wrong, one would be enough", Albert Einstein upon hearing of the book "Hundred Authors Against Einstein"

Steven E. Koonin

On Jun 2, 2025, at 16:30, Judith Curry <curry.judith@gmail.com> wrote:

I still think it is a tough case to make that 5 scientists decide an assessment report authored by 500 scientists and reviewed by NASEM is scientifically inadequate, no matter how much cherry picking we identify. If we make the case that the NCA5 process has been politicized, then I think we have a more credible as a critique

On Mon, Jun 2, 2025 at 9:08 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I drafted the attached cover letter and outline before I saw Judy's draft. There are some obvious ways to fuse them.

I worry about getting too far out of our lane and also getting too political. Stick with the science and judge NCA5 as a scientific document informing policy – that's really all we should do.

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Monday, June 2, 2025 10:33 AM

To: Steven Koonin <steven.koonin@gmail.com>

Cc: John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>;

Roy Spencer <roywspencer@hotmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Josh Loucks <loucksj14@gmail.com>

Subject: Re: an early take on NCA5 Chapter 1

See attached (note, this is pretty much all i can do for next 24 hours, need to be in hurricane report mode). Let me know what you think

On Sun, Jun 1, 2025 at 3:21 PM Steven Koonin <steven.koonin@gmail.com> wrote:

So how would you frame and support that more general argument?

Steven E. Koonin

On Jun 1, 2025, at 17:46, Judith Curry <curry.judith@gmail.com> wrote:

My current thinking on this is to make an argument that the NCA5 is not fit for the purpose of informing policy making: "assisting the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

I think this is the bigger issue than actual "errors" in the report -- the whole thing is based on flawed assumptions, and they're looking at the wrong things. We could find 200 errors in the report and that still wouldn't kill it.

On Sat, May 31, 2025 at 1:53 PM judith curry
<curry.judith@gmail.com> wrote:

I'm working on some introductory big picture text for our review for your consideration. Will have draft on Monday

Sent from my iPhone

On May 31, 2025, at 7:54 AM, Steven Koonin
<steven.koonin@gmail.com> wrote:

A read-through of NCA5 Chapter 1 shows some endemic issues we should flag (some of these already mentioned). Plenty of examples of each in the text.

- confusion of climate change vs changing climate (i.e., attribution of all climate changes to anthropogenic forcing)

- confusion of weather vs climate (the plural of anecdote is not evidence)

- no mention of uncertainties or significance in trends cited

- taking model results at face value (have they pruned the ensemble used?)

- no setting of scale for big numbers (e.g., dollars of climate damage relative to GDP)

- truncation of data records (ignoring the inconveniently warm 1930s)

- use of extreme, implausible scenarios (even though AR6 had already declared SSP8.5 and 7 implausible)

- no mention of benefits of climate change or how they net against disbenefits?

...

SEK

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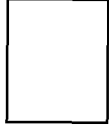
Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
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From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Monday, June 2, 2025 9:49 AM
To: Steven Koonin
Cc: John Christy; Judith Curry; Roy Spencer; Ross McKittrick; Josh Loucks
Subject: Re: an early take on NCA5 Chapter 1

I want to second what John said. Don't we need both facts and logic to convince people NCA 5 is not on solid ground? In other words, we can show that the reasoning is incomplete or unsupported (and we should), but we should also provide data to show what the missing pieces look like. I thought the DOE report was excellent on this front, so it might only require cross-referencing the report.

One more thing I want to highlight is the phenomenon in NCA 5 of providing citations for uncontroversial findings but offering no citations for controversial findings (the latter being surrounded by the former). The best example I've seen so far is in the summary paragraph of the wildfires page:
<https://nca2023.globalchange.gov/chapter/focus-on-2/>

Is this a widely used tactic throughout NCA 5? It reminds me of the way people often sandwich a critique between two compliments. Makes the tough part easier to swallow.

9:41



28.5).^{2, 3, 4} Development in the
has greatly expanded the wildland-
interface (KMs 12.2, 28.5)⁵ are
human-caused ignitions, jeopardizing
people, property, and infrastructure.
In recent years, climate change has
contributed to very large and severe fires
that have replaced moderate-severity fire with

On Mon, Jun 2, 2025 at 9:28 AM Steven Koonin <steven.koonin@gmail.com> wrote:

Other assumptions besides “models are infallible”:

- weather is climate
- all changes are anthropogenic
- the past started in 1950
- extreme events are increasing
- US mitigation can stop the climate from changing
- ...

I wouldn't call them assumptions, because I think the authors know well they're incorrect. Misrepresentations is a better word.

And note that beyond asserting the report says these things, we've got to give specific examples from the report.

Steven E. Koonin

On Jun 2, 2025, at 07:25, John Christy <climateman60@gmail.com> wrote:

Judy

I agree that the assumptions are more or less religious beliefs about climate change. What are those assumptions? For example, “Climate models are fit-for-purpose.” Shouldn't we then demonstrate with facts that the assumption is false? (Such as we've done in the Climate Report)? As a result, the NCA5 would be shown to be not credible.

John C.

Sent from my iPhone

On Jun 1, 2025, at 5:21 PM, Steven Koonin <steven.koonin@gmail.com> wrote:

So how would you frame and support that more general argument?

Steven E. Koonin

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<curry.judith@gmail.com> wrote:

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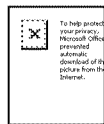
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- use of extreme, implausible scenarios (even through AR6 had already declared SSP8.5 and 7 implausible)

- no mention of benefits of climate change or how they net against disbenefits?

...

SEK



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Ross McKittrick [ross.mckittrick@gmail.com]
Sent: 5/22/2025 1:11:36 PM
To: Roy Spencer [roywspencer@hotmail.com]
CC: Steven Koonin [steven.koonin@gmail.com]; John Christy [climatemanager60@gmail.com]; Judith Curry [curry.judith@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]
Subject: Re: and here's the replacement for Fig. 5.3...

Since we have the Scaffeta figure we don't need the Heritage surface time series graph. I can swap in the replacement with this text

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3.

Then show the updated Fig 5.4 with text

The discrepancy was flagged as a serious inconsistency in the first US Climate Change Science Program report (Karl et al. 2006) and has been mentioned in every IPCC report since, but it has gotten worse over time, and the bias is now global. McKittrick and Christy (2020) compare tropospheric warming trends in CMIP6 climate models to observed trends from satellites, weather balloons and reanalysis systems. Figure 5.4 presents the comparisons with data updated to 2024. Every model overpredicts the average observed warming trend in both Lower- and Mid-Troposphere layers, both globally and in the tropics. In most individual models the bias is statistically significant and on average across models it is highly significant. McKittrick and Christy (2020) also show that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If future climate models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble

Then leave out the new Fig 5.5. Would that work?

On Thu, May 22, 2025 at 8:15 AM Roy Spencer <roywspencer@hotmail.com> wrote:

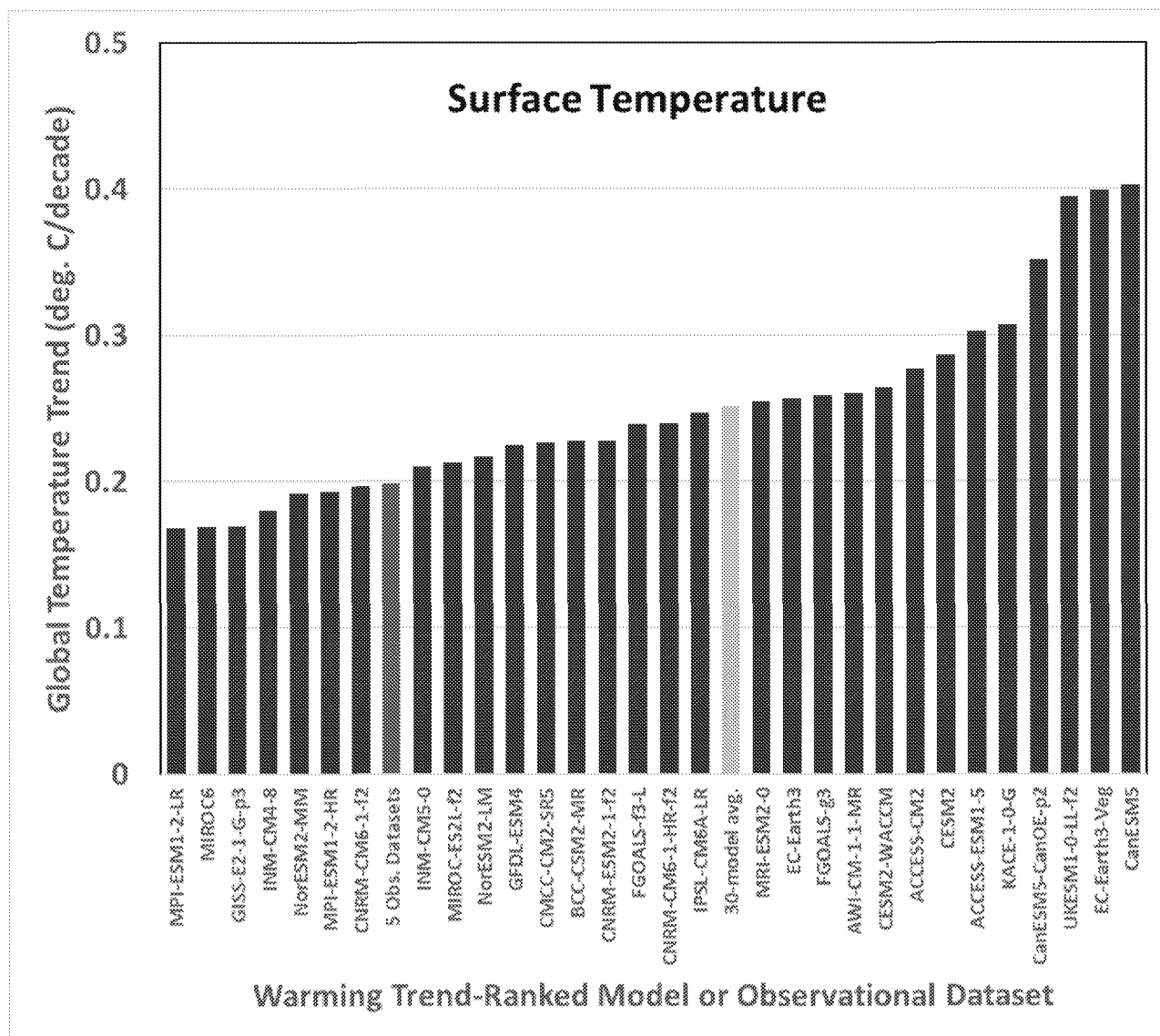


Fig. 5.3 Global surface air temperature trends, 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue.

From: Steven Koonin <steven.koonin@gmail.com>

Sent: Thursday, May 22, 2025 7:00 AM

To: 'Roy Spencer' <roywspencer@hotmail.com>; 'John Christy' <climateman60@gmail.com>; 'Ross McKittrick' <ross.mckittrick@gmail.com>; 'Judith Curry' <curry.judith@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>

Subject: RE: CORRECTED new Fig. 5.5 (note the 38-model average bar)

Like this figure – it vividly makes the point.

SEK

From: Roy Spencer <roywspencer@hotmail.com>

Sent: Thursday, May 22, 2025 7:05 AM

To: John Christy <climateman60@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Judith Curry <curry.judith@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>
Subject: CORRECTED new Fig. 5.5 (note the 38-model average bar)

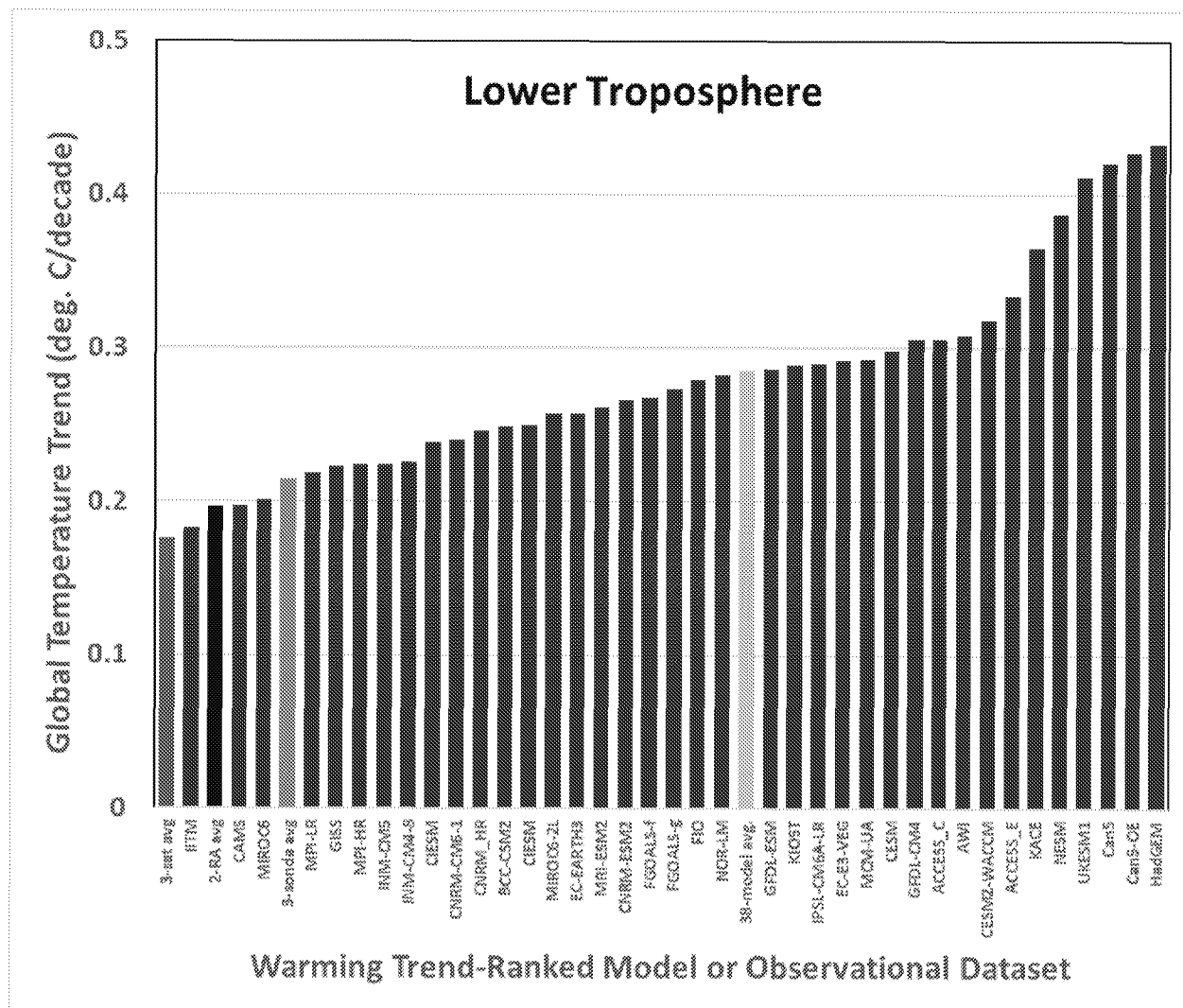


Fig. 5.5 Global lower-tropospheric temperature trends, 1979-2024, from various CMIP6 climate models (red, 38-model average in orange); the average of three satellite datasets (blue); the average of two reanalysis datasets (black); and the average of three radiosonde datasets (green).

From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Thursday, August 7, 2025 5:10 PM
To: Steven Koonin
Cc: John Christy; Judith Curry; Roy W. Spencer; Josh Loucks; Woods, Andrea; Ison, Jeremy T.; Travis Fisher
Subject: Re: and now NASEM gets into the act

Deadline for submissions is Aug 27.

According to the press release (<https://x.com/JunkScience/status/1953549045248491887>) it "will be completed and publicly released in September".

So no, it will not receive anything like the same level of scrutiny as our report.

This looks to me like they're injecting themselves into a political battle. "Endangerment" is not a scientific question, it's a legal/value judgment, and no one asked Marcia McNutt to weigh in. I think there's 0% chance they will come back with any other answer than that GHG emissions endanger the public.

On Thu, Aug 7, 2025 at 4:43 PM Steven Koonin <steven.koonin@gmail.com> wrote:

<https://www.nationalacademies.org/our-work/anthropogenic-greenhouse-gases-and-us-climate-evidence-and-impacts>

I think this is a good thing – it will open the dialog.

Question is whether the resultant report will receive the same scrutiny our report has gotten.

Steve Koonin

From: Ross McKittrick [rmckitri@uoguelph.ca]
Sent: 8/7/2025 1:59:07 PM
To: Bruce Calvert [brucetcalvert@gmail.com]; christy@nsstc.uah.edu; curry.judith@yahoo.com; Steven Koonin [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=aca60f0a4c1d404bb613caabcb9e05b1-koonin]; roy.spencer@nsstc.uah.edu
Subject: Re: Antarctic sea ice loss overestimated by up to 4 million km²

Dear Bruce

Thanks for your note and good to hear from you again. These are very interesting points. I encourage you to submit them through the public comment docket at

<https://www.federalregister.gov/documents/2025/08/01/2025-14519/notice-of-availability-a-critical-review-of-impacts-of-greenhouse-gas-emissions-on-the-us-climate>

if you haven't already. We didn't address cryosphere issues and I can't promise we will be able to do the topic justice in the revision. But to your point about funding for data collection, we plan to offer advice (even if unsolicited) about future priorities for the USGCRP. One topic we all agree on is the need to address the underfunding of some key monitoring systems, and the need for new initiatives to examine historical archives and records so the data can be digitized and made available for research. If you could add some specific recommendations in your submission about what you'd like to see done to improve sea ice records, we will do what we can to get the information into the right hands.

Cheers,
Ross

Dr. Ross McKittrick
Professor of Economics
Department of Economics and Finance
rossmckittrick.com



University of Guelph | Guelph ON Canada N1G 3P9

From: Bruce Calvert <brucetcalvert@gmail.com>
Sent: Wednesday, August 6, 2025 11:28 PM
To: christy@nsstc.uah.edu <christy@nsstc.uah.edu>; curry.judith@yahoo.com <curry.judith@yahoo.com>; koonin@stanford.edu <koonin@stanford.edu>; Ross McKittrick <rmckitri@uoguelph.ca>; roy.spencer@nsstc.uah.edu <roy.spencer@nsstc.uah.edu>
Subject: Antarctic sea ice loss overestimated by up to 4 million km²

CAUTION: This email originated from outside of the University of Guelph. Do not click links or open attachments unless you recognize the sender and know the content is safe. If in doubt, forward suspicious emails to IThelp@uoguelph.ca.

Dear Drs. Christy, Curry, Koonin, McKittrick, and Spencer,

I enjoyed reading your recent critical review on the impacts of greenhouse gas emissions.

I noticed that your paper is missing a discussion of uncertainty in sea ice datasets, particularly prior to the satellite era. This is an often overlooked aspect of uncertainty in climate science.

Unfortunately, the existing commonly used data products have serious issues. The biggest problem is that the

most commonly used dataset, HadISST2, is entirely based on a German 1929-1939 Antarctic sea ice atlas. From what I can tell, that atlas is based on observations that include the 1929-1931 British, Australian and New Zealand Antarctic Research Expedition; whaling observations; and 1938-1939 observations from when the Nazis were trying to claim New Swabia for the third reich. Unfortunately, this atlas was misinterpreted to be representative of sea ice conditions during 1929-1939 period rather than representative of maximum sea ice extent conditions to warn sailors of potential danger.

As a result, about 4 million km² of Antarctic sea ice were "lost" prior to the satellite era according to HadISST2. This "loss" exceeds what has been observed globally since the start of the satellite era. However, four recent reconstructions ([link1](#);[link2](#);[link3](#);[link4](#)) all suggest that this massive ice loss did not occur.

This issue with HadISST2 is problematic for a few reasons. Firstly, it weakens the ability to compare the performance of climate models at simulating observed Antarctic sea ice loss. Secondly, HadISST2 is used by most global temperature datasets including HadCRUT5, GloSAT, Berkeley Earth, GISTEMP, NOAAGlobalTemp (indirectly via ERSST), China-MST3.0-Imax (indirectly via ERSST), and CMA-GMST. This is particularly problematic for Berkeley Earth and my two datasets ([link1](#);[link2](#)) based on how these datasets try to account for the temperature impacts of sea ice loss. Furthermore, ERA5 sea ice concentrations prior to the satellite era are largely based on HadISST2, so this issue affects ERA5 as well.

This issue with HadISST2 will be briefly discussed in a community science paper that I am coauthoring and should become available later this year. Please feel free to cite or share this paper once it is made publicly available.

Beyond HadISST2, other pre-satellite sea ice datasets have issues. The National Snow and Ice Data Center's (NSIDC's) G10010v2 dataset, which uses quite a few more observations than HadISST2 for the northern hemisphere, has serious erroneous data issues such as due to coding errors. This includes assigning sea ice data to the wrong calendar month from 1901 to 1956, too much Bering Sea ice in April 1901, subtropical sea ice in June 1962, missing sea ice for many months in the Gulf of St. Laurence and Sea of Okhotsk (e.g., January 1920). COBE-SST3, another sea ice dataset (as well as a sea surface temperature dataset), which is used by the COBE-STEMP3 global temperature dataset, uses sea ice estimates from G10010v1, so inherits some erroneous data issues, such as assigning sea ice to incorrect longitudes east of Greenland for August 1874. I have attached some images so that you can visualize these issues.

Unfortunately, the NSIDC has not had sufficient funding either under the current U.S. administration nor under the previous one, to fix the issues with their NSIDC dataset. Beyond erroneous data issues, none of these pre-satellite sea ice datasets provide uncertainty estimates. The 2014 HadISST2 paper mentioned plans to produce uncertainty estimates, but there was no follow-up to those plans.

I fear that if there are no improvements to sea ice datasets then the scientific community will continue to use HadISST2, overestimate sea ice loss, and underestimate uncertainty in sea ice concentrations. I don't know what power you have to influence climate research funding decisions, but if you had any influence then I would suggest the following:

1. Provide funding to the NSIDC to complete a version 3 of their G10010 northern hemisphere sea ice dataset.
2. Provide funding to the NSIDC to complete a comparable data product to G10010 for the southern hemisphere. There are many Antarctic sea ice observations that have not been incorporated into global pre-satellite sea ice datasets, including early satellites, whaling observations ([link1](#);[link2](#)), and Antarctic expeditions ([link1](#);[link2](#);[link3](#)).
3. Ensure that the NSIDC has access to Special Sensor Microwave Imager/Sounder (SSMIS) data. This is an important data product to track sea ice trends and is also used as the reference for many pre-satellite sea ice data products. I am glad that the U.S. administration has decided to extend data access, but continued reports of the U.S. administration planning to end data access are concerning.

I have no financial interest in the NSIDC receiving additional funding. I am merely someone who does temperature research as a hobby and is concerned about the current state of pre-satellite sea ice datasets. Also, please do not publicly share the contents of this email until the community science paper is published later this year, as I don't want to cause issues for that process.

Best regards,
Bruce Calvert

From: John Christy <climateman60@gmail.com>
Sent: Wednesday, July 2, 2025 11:29 AM
To: Ross McKittrick
Cc: Steven Koonin; Judith Curry; Roy W. Spencer; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: AP on NCA reports disappearing

Hayhoe - the same person who led the climate model evaluation section of NCA4 but who owns a company that makes money off of selling climate model output.

Steve - I think we should add a line in our NCA5 review at the very end of the evaluation of NCA4's Fig. ES.5 (just above section 2, page 9) that says, "This illustrates the degradation of credibility that occurs when authors have final review-authority over their own text."

John C.

On Wed, Jul 2, 2025 at 10:18 AM Ross McKittrick <ross.mckittrick@gmail.com> wrote:

Well if Borenstein is down to getting scare quotes from Holdren and Hayhoe I'd say the story doesn't have much legs.

NCA5 "really is the primary source of information for any city, state or federal agency who's trying to prepare for the impacts of a changing climate," said Texas Tech climate scientist Katharine Hayhoe

I doubt even her own town, much less state, uses NCA5 for planning purposes.

On Wed, Jul 2, 2025 at 11:14 AM Steven Koonin <steven.koonin@gmail.com> wrote:

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The media are heating up on all of this. I hope they'll focus on the factual content of what we've written, but doubt that they will.

Steve Koonin

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Wednesday, July 2, 2025 12:07 PM
To: Steven Koonin
Cc: John Christy; Ross McKittrick; Judith Curry; Roy W. Spencer; Josh Loucks; Seth Cohen
Subject: Re: AP on NCA reports disappearing

I'll have some updates on this tomorrow! We are likely going to open up a separate DOE comment portal for the DOE report (the May 28 CWG report), and we are also likely to put the report through internal DOE concurrence first.

If you all know of any particular people of offices within DOE that should be included, please flag them for me on our call. Even if you expect them to be antagonistic, I'd still like to include everyone who has the relevant expertise.

On Wed, Jul 2, 2025 at 11:47 AM Steven Koonin <steven.koonin@gmail.com> wrote:

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Our report could be accused of the same thing, so we need something to mitigate that. Open the peer review comments to the public? Use AI to group/summarize them?

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Subject: Re: AP on NCA reports disappearing

Likewise I don't think adding the sentence is helpful. If people complain that we have final authority over our own final text we can point out that that is the standard for NCA and IPCC so if people don't like it they should have brought the matter up long ago.

If the CWG report is currently going through Inter-Agency review, does that mean that we will soon have a stack of helpful comments to wade through and if so, will that be something needing to be done before the report is released mid-July? Perhaps Travis you could update us tomorrow.

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Steve Koonin

From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Wednesday, July 2, 2025 11:19 AM
To: Steven Koonin
Cc: Judith Curry; Roy W. Spencer; John Christy; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: AP on NCA reports disappearing

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Steve Koonin

From: Ross McKittrick [rmckitri@uoguelph.ca]
Sent: 8/13/2025 10:32:44 PM
To: Borenstein, Seth [SBorenstein@ap.org]
CC: Phillis, Michael [MPhillis@ap.org]; Judith Curry [curry.judith@gmail.com]; roy spencer [roywspencer@hotmail.com]; John Christy [climateman60@gmail.com]; Steve Koonin [steven.koonin@gmail.com]
Subject: Re: AP seeking your reaction to comments on DOE document from cited scientists and outside scientists

Here is a statement on behalf of the report's authors.

The report's preface states clearly that it is not meant to be a comprehensive review of climate science but rather is focused on important data and topics that have been under-reported or overlooked in media and political discussions.

Generic accusations of bias or cherry-picking are not helpful for serious scientific discussions. The report has been presented for public comment and expert review and we will respond seriously to all serious criticisms, making revisions as warranted.

Some errors, such as the one you cite about Arctic sea ice, have already been brought to our attention and will be corrected.

Note also that some self-citation is inevitable since we are writing about topics within our areas of expertise.

Dr. Ross McKittrick
Professor of Economics
Department of Economics and Finance
rossmckittrick.com



University of Guelph | Guelph ON Canada N1G 3P9

From: Borenstein, Seth <SBorenstein@ap.org>
Sent: Wednesday, August 13, 2025 2:37 PM
To: Ross McKittrick <rmckitri@uoguelph.ca>
Cc: Phillis, Michael <MPhillis@ap.org>
Subject: AP seeking your reaction to comments on DOE document from cited scientists and outside scientists

CAUTION: This email originated from outside of the University of Guelph. Do not click links or open attachments unless you recognize the sender and know the content is safe. If in doubt, forward suspicious emails to IThelp@uoguelph.ca.

Hello and we hope you are doing well.

Because of the discussion and controversy surrounding the July EPA proposed rescission of the Endangerment Finding and the Department of Energy's A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate and claims by some scientists whose studies were cited that their work was misinterpreted by the documents, The Associated Press sent emails to more than 350 scientists this month, asking a series of questions. About 60% of those scientists had their work cited and the other 40% were outside scientists asked about the quality of the reports.

Here's a quick summary of our results. Can you please acknowledge receipt of this and respond by the end of business day Thursday as we plan to publish in the next few days.

Of the 59 responses we got, 50 were negative and six were positive. Scientists criticized the report for cherry-picking data and information – with 16 different scientists using a variation of the phrase cherry pick in 28 different instances.

Scientists, both those from outside and those whose work was cited, said the reports were biased, misleading and do not reflect the current state of knowledge about climate change.

In 15 cases, cited scientists said the reports misused, misinterpreted or took their work out of context. Six scientists used the word “misleading” to describe the sections where their work was cited.

Among the many problems scientists pointed out, on page 90 the DOE report talked of a 5% decrease in Arctic sea ice since 1980, with a link to a document that clearly is marked Southern Hemisphere and it's for July only, not yearly average. On an annual basis Arctic – not Antarctic – sea ice has decreased more than 40% since 1980, NSIDC data shows. One researcher called the work sloppy, while another said the DOE section was misleading and actually false. One scientist disputed the part in the DOE document that said fire acres burned increased “but only until about 2007” and said her calculations show a smaller increase post 2007. AP looked at NIFC acreage data and found three years since 2007 with more acres burned than 2007: 2015, 2017 and 2020. And the 10-year average of 2015-2024 is 7.5 million acres burned while the 10-year average from 1998-2007 is 6.5 million acres.

There are more. Here are a few quotes that we may be using in the story:

“It is almost a user’s guide on how to lie with figures,”

“The DOE and EPA reports are fundamentally flawed (mostly wrong and riddled with cherry-picked results that distort the scientific consensus). These documents do not reflect genuine scientific rigor, but rather a misleading reinterpretation of peer-reviewed research.”

“The citation to our work was intentionally misleading,”

“I’m cited three times, once accurately.”

Of course there were six scientists who praised the work and we will reflect that.

We seek your thoughts on what we found and what the scientists are saying. Do you consider your report biased? If not, why was it written by only known climate change skeptics?

Does what mainstream scientists say about this matter?

And is there a reason why reporters authors referred more to their work than others, with more than two dozen McKittrick citations?

Thanks for your consideration.

Seth and Mike

Seth Borenstein
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The Associated Press

Advancing the Power of Facts

"There are only two forces that can carry light to all corners of the globe — only two — the sun in the heavens and The Associated Press down here."

- Mark Twain

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communication is strictly prohibited. If you have received this communication in error, please notify The Associated Press immediately by telephone at +1-212-621-1500 and delete this email. Thank you.

From: Judith Curry <curry.judith@gmail.com>
Sent: Wednesday, April 23, 2025 8:48 AM
To: Roy Spencer
Cc: Steven Koonin; Ross McKittrick; Travis Fisher; John Christy
Subject: Re: Apr 20 update

Here's a paragraph from my book

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing atmospheric composition by increasing the emissions of CO₂ and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

I think this para puts anthro CO₂ into the appropriate context

On Wed, Apr 23, 2025 at 3:59 AM Roy Spencer <roywspencer@hotmail.com> wrote:

All:

I've made some edits to Steve's document (attached).

The first (rather large) edit has to do with the implication that climate change is only due to changes in the radiative energy balance of the Earth, which I (and Dick Lindzen) disagree with. How to handle this, though, is not that obvious to me. I realize we are addressing human influences on climate, but I don't think we should accept such an anthropocentric view of climate change at the outset... This comes up later, too, in the discussion of global radiative forcing since the 1700s... We have no clue what kinds of other energy imbalances (either at the surface or at top-of-atmosphere) might have been occurring due to Nature since the 1700s.

Again, I'm open to suggestions. Maybe such issues are not necessary to mention if even the putative human forcings lead to non-damaging impacts (?)

-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Tuesday, April 22, 2025 11:05 PM
To: 'Ross McKittrick' <ross.mckittrick@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'John Christy' <climateman60@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Judith Curry' <curry.judith@gmail.com>
Subject: RE: Apr 20 update

Attached is my take on an integrated Part 1 (together with a modest introduction). I've incorporated relevant material from others.

1. See if you like the narrative arc, which to me feels pretty natural. Note that the subsections turned out to have somewhat different titles
2. Most problematic for me is the technical level. Trying to avoid too much “Climate 101”, but some of the material, particularly in Parts 2 and 3 will get pretty technical
3. I’m feeling like it lacks punch. “So what” is missing
4. Obviously, the mechanics need work. Formatting, citations, better figures, ...
5. If you all aren’t too dissatisfied with this, I’d propose doing a similar job on Part 2 in the next few days.

SEK

From: Ross McKittrick <ross.mckittrick@gmail.com>
Sent: Sunday, April 20, 2025 8:09 PM
To: Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; Judith Curry <curry.judith@gmail.com>
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The new outline is (bold denotes draft posted)

Part I: Human influence on the climate

- 1 Components of anthropogenic radiative forcing and their history to date
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- 3 Aerosols and the uncertainties associated with them

Part II: Climate response to anthropogenic influence

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- 6 Uncertainties in analysis of attribution**
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- 8 Sea level rise

Part III: Impacts on ecosystems and society

- 9 Managing risks of extreme weather**
- 10 Mortality risk from extreme heat and cold
- 11 Climate change and US agriculture**
- 12 Climate change and global greening
- 13 Climate change and economic growth**

- 14 Estimates of the Social Cost of Carbon
- 15 US vehicle-based CO2 emissions and the global climate

Steve: can you draft 1 & 3?

Judy: hoping you can do 8, 10 and 14 (I have info on 14 as well.)

John I think you have something on 15.

Cheers,
Ross



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
<http://www.cfanclimate.net>

From: Ross McKittrick <ross.mckitrick@gmail.com>
Sent: Wednesday, April 23, 2025 8:49 AM
To: Roy Spencer
Cc: Steven Koonin; Travis Fisher; John Christy; Judith Curry
Subject: Re: Apr 20 update

Thanks Steve and Roy. I have a few wording suggestions but am off to a meeting so I'll write later. Travis and I had a meeting with Secretary Wright yesterday. I'll let Travis provide a more complete summary but my takeaway was:

- Chris was unaware of the problems we had encountered until we briefed him
- The current deadline and lack of direction conflicts with his vision of the project
- He is going to try to get more time for us; and there might be an option which gives us a lot more time
- He wants us to have the time and support to produce a substantive document with our names on it. He understands why if we are held to an Apr 30 deadline we would not be able to do that.
- More to come as he digs into the situation.

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From: Judith Curry <curry.judith@gmail.com>
Sent: Wednesday, April 23, 2025 7:48 AM
To: Roy Spencer <roywspencer@hotmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; Ross McKittrick <ross.mckittrick@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; John Christy <climateman60@gmail.com>
Subject: Re: Apr 20 update

Here's a paragraph from my book

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean produce exchanges of energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing atmospheric composition by increasing the emissions of CO₂ and other greenhouse gases and by altering the concentrations of aerosol particles in the atmosphere.

I think this para puts anthro CO₂ into the appropriate context

On Wed, Apr 23, 2025 at 3:59 AM Roy Spencer <roywspencer@hotmail.com> wrote:
All:

I've made some edits to Steve's document (attached).

The first (rather large) edit has to do with the implication that climate change is only due to changes in the radiative energy balance of the Earth, which I (and Dick Lindzen) disagree with. How to handle this, though, is not that obvious to me. I realize we are addressing human influences on climate, but I don't think we should accept such an anthropocentric view of climate change at the outset... This comes up later, too, in the discussion of global radiative forcing since the 1700s... We have no clue what kinds of other energy imbalances (either at the surface or at top-of-atmosphere) might have been occurring due to Nature since the 1700s.

Again, I'm open to suggestions. Maybe such issues are not necessary to mention if even the putative human forcings lead to non-damaging impacts (?)

-Roy